Factors Affecting

SNOWMELT and STREAMFLOW

FRASER EXPERIMENTAL FOREST

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A report on the 1946–53 Cooperative Snow Investigations at the Fraser Experimental Forest, Fraser, Colo., by W. U. Garstka, L. D. Love, B. C. Goodell, and F. A. Bertle. March 1958.

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SNOWMELT and STREAMFLOW

By W. U. Garstka, Engineer, Bureau of Reclamation,
L. D. Love and B. C. Goodell, Foresters, Forest Service,
and F. A. Bertle, Engineer, Bureau of Reclamation.

ABSTRACT

This report summarizes the work done and the analyses made with data collected at the Fraser Experimental Forest, Fraser, Colo., during the snowmelt seasons of 1947 to 1953, inclusive. The Bureau of Reclamation and the Forest Service collaborated in these cooperative snow investigations. Comparisons between the catch in Sacramento-type storage precipitation gages and the accumulation of snow on the ground indicate that the gage catch was generally deficient. Charts are presented comparing degree-days computed from daily maximum and minimum temperatures with degree-days indicated by thermograph traces. Analyses of the runoff hydrographs show the major importance of long-term recession flows in the snowmelt hydrograph. Relations are developed between the daily snowmelt hydrograph and the melt-causing meteorological factors that lead to the development of techniques for forecasting the shape of the snowmelt hydrograph on a daily basis. The relation of area of snow cover to the resulting hydrograph is explored for one year when detailed mapping of the snow-covered area was pursued. The effect of evaporation during the snowmelt season is analysed by use of Light's equation. Instrumentation at the Experimental Forest is described and samples of available data tabulations are shown. Although this report concludes the cooperative snow investigations, the Forest Service is continuing its research work at the Experimental Forest to determine the effect of forest management on the water yielded from this snow-fed drainage basin.

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FOREWORD

The excellent collaboration between the Bureau of Reclamation and the Forest Service, as is evidenced by this report on the Cooperative Snow Investigations at the Fraser Experimental Forest, had its inception at the "First Conference of Engineers" [75] [1] of the then newly organized Reclamation Service, which was held at Ogden, Utah, September 15 to 18, 1903.

Gifford Pinchot, Chief Forester of the Forest Service, spoke at this conference and his presentation is quoted in part as follows: [2]

> For the present much the most important use of the forest reserves is to supply water to the irrigator, and their utility in this respect should be preserved in every possible way. This use, too, will increase with time, and it will become more and more evident that the foundation of the irrigation development of the West lies in the wise administration of the forest reserves. Not only can the present supplies of water be conserved by the right handling of the forest, but there is no question whatever that in many localities they may be largely increased.

Although few men are alive today who comprised the Reclamation Service and the Forest Service on the date when Gifford Pinchot attended the meeting at Ogden, the basic concepts on development of natural resources which inspired the workers of that day stand forth today with undiminished brilliance as guiding lights in the endeavor to attain more intensive and efficient utilization of the Nation's water resources.

[1] Numbers in brackets refer to list of references beginning on page 185.

[2] Reference 75, page 120.

ACKNOWLEDGMENTS

This, the fourth report, is the complete report on the cooperative snow investigations which were conducted during the period 1946 through 1953, at the Fraser Experimental Forest near Fraser, Colo., by the Commissioner's Office, Denver, Colo., of the Bureau of Reclamation, U. S. Department of the Interior, and the Rocky Mountain Forest and Range Experiment Station, Forest Service, U. S. Department of Agriculture.

BUREAU OF RECLAMATION

For the Bureau of Reclamation, these investigations were conducted under the general direction of L. N. McClellan, formerly Assistant Commissioner and Chief Engineer, and under the broad supervision of J. R. Riter, Chief Development Engineer, Division of Project Investigations. W. U. Garstka was responsible throughout for the technical aspects of this investigation. The first report [84] was prepared under the administrative supervision of H. P. Dugan; the second report [85] under L. F. Maca; and the third report [86] under H. S. Riesbol. This final report was prepared for publication under the general direction of Grant Bloodgood, Assistant Commissioner and Chief Engineer.

Construction of and improvements to certain hydrologic instruments and recalibration and maintenance of recorders were performed by the Division of Engineering Laboratories under the direction of W. H. Price, Chief. The compilation of this report was facilitated through the cooperation of W. T. Moran, formerly Chief, Chemical Engineering Laboratory Branch. Editorial work was performed by M. T. York of the Division of Administrative Services.

FOREST SERVICE

For the Forest Service, these investigations were conducted under the general direction of Dr. W. G. McGinnies, and later of Raymond Price, Directors, Rocky Mountain Forest and Range Experiment Station. Dr. H. G. Wilm, Silviculturist, was responsible for technical aspects of the program until January 1948, at which time he was succeeded by Dr. L. D. Love, Forester. During 1946–49, Mr. B. C. Goodell, Forester, was in immediate charge of the installation and operation of field instrumentations. During 1950–52, Mr. E. G. Dunford, Forester, operated the field instrumentations and assisted in the preparation of the second report [85].

OTHER AGENCIES

The St. Louis Creek stream gaging station is operated and maintained by the Geological Survey, U. S. Department of the Interior, under cooperative agreement with the Colorado State Engineer. The Fraser, Colo., Climatological Data Station, the Redcliff, Colo., Hygrothermograph Station, and the Solar Radiation Station at the Bureau of Reclamation's Granby Pumping Plant of the Colorado-Big Thompson Project, are operated in cooperation with the Weather Bureau, U. S. Department of Commerce.

The authors wish to express their appreciation especially to Mrs. P. P. Thomason, formerly with the Bureau of Reclamation, for her contributions to this investigation, and to the following people, arranged alphabetically, both the stalwart field men who performed their tasks in the snowfields, often under rigorous conditions, and to the analysts who carried through the extensive computations with accuracy and devotion.

For the Bureau of Reclamation

Barnes, B. S.
Bennet, G. C.
Bezler, M. D.
Braungardt, D. K.
Byrne, G. P.
Daum, C. R.
Fontecchio, Mrs. Dessi
Ford, P. M.
Gates, A. C.
Goodson, J. L.
Highley, G. R.
Honnold, J. L.
Kotz, S. E.
Lancaster, D. M.
Lara, J. M.
Lewis, Frank
Lupton, F. R.
Mohr, H. L.
Morgan, E. D.
Neilsen, E. J.
Newell, L. M.
Newland, Walter
Parker, W. O.
Robinson, Mrs. E. P.
Spenard, Oscar
Thomas, C. W.
Wilson, B. F.
Young, J. L.. Jr.

For the Forest Service

Alexander, R. R.
Brown, H. E.
Florquist, W. L.
Innes, Mrs. Jean
Kielhorn, Richard
Kreycik, Mrs. John
Lexen, B. R.
Monninger, L. V.
Myers, C. A.
Neumann, R. H.
Niemi, Hugo
Pole, Rupert
Riegels, Mrs. Cora
Smith, Charles
Wennerstrom, Mrs. Dorothy
Wright, Eric

Foreign Trainees of the Bureau of Reclamation

Anderson, David—Australia
Lanz-Lopez, Manuel—Venezuela
McCutchan, A. I.—Australia

SECTION 1—INTRODUCTION

Runoff from melting snow during a short period in the spring provides most of the water supply in the western United States, but is not timed to meet the requirements for crop production, hydroelectric power generation, municipal water, and other multiple-purpose objectives. This situation has led to the development of an irrigated economy based upon the reservoir control and management of the water resources in snow-fed drainage basins. Thus, a basic understanding of snow and of the processes by which the disappearing snow pack is converted to streamflow is necessary for efficient management of irrigation and multiple-purpose projects.

The watersheds of the central Rocky Mountains exert a commanding influence on irrigation and other water uses throughout a major portion of the arid West. The Colorado River flows to the west, the Rio Grande to the south, the Arkansas to the east, and major tributaries of the Missouri River to the north and east. In the Colorado River Basin alone, over three-quarters of the total annual yield flows from the high-altitude, forested drainage basins of Colorado and Wyoming.

Since the objectives of the Bureau of Reclamation and the Forest Service both relate to the most efficient utilization of the water resources, the collaboration of these two agencies in this snow investigation was a natural development. A thorough understanding of the processes, by which accumulated winter precipitation in the form of the snow pack is converted to spring streamflow in the channel, is fundamental to the research and operations programs of both the Bureau of Reclamation and Forest Service.

Specifically, the objectives of these snow investigations were:

a. Measurement of the total winter precipitation.

b. Determination of the amount of snow in storage on a drainage basin in terms of water equivalent, its distribution over the basin, and its disappearance as the melt season progressed.

c. Development of methods of rapid evaluation of heat availability for use in predicting runoff from snowmelt, both in project planning and in actual reservoir operation.

d. Development of a technique capable of routine use; first, to account for, and second, to forecast losses from snow storage, which may occur either as snowmelt or as evaporation.

The foregoing objectives are related directly to the development of new methods and improvement of existing methods of forecasting the runoff from snowmelt, not only seasonal water yield runoff but also rate of runoff. The seasonal water yield forecasts deal with prediction of a total volume of flow for a given period, e. g., April to July. They do not take into account the rates of melt or the distribution in time within the forecast period of the rate of inflow to reservoirs.

On the other hand, rate of runoff forecasts from snowmelt deal with short-term daily forecasting of the water yielded by a drainage basin on which snowmelt is taking place. Rate of runoff forecasts in certain areas may also be complicated by rainfall that occurs either before or during the snowmelt period. Both types of forecasts are used in both project planning and in the operation of facilities depending upon water resources.

Forecasts are used in project planning to assist in deciding upon the capacity of the reservoirs and in allocating portions of that capacity among the various multiple purposes for which the project is designed. Rate of runoff from snowmelt forecasts are used in project planning in estimating hypothetical floods, on which decisions are reached relating to the reservoir allocations for flood control, protection of the structures, and on the carrying capacity of outlet and spillway structures, especially the latter. An understanding of the processes of snowmelt conversion to streamflow in the absence of rain sets the foundation for development of methods of estimating runoffs which would occur under extreme conditions of combined rainfall and snowmelt floods.

Seasonal water-yield forecasts are used extensively in irrigation and multiple-purpose project

operations. If snow surveys indicate that the expected water yield is considerably less than normal, the usual practice is to allocate a certain volume of water per water-right acre. The decision is then left, usually, to the individual irrigator as to the type of cropping, distribution of water demands, and frequency of irrigation he personally will follow. Seasonal water-yield and annual water-yield forecasts are used as the basis for setting up hydroelectric energy generation schedules. In the West, whatever utilization there may be of the water resource takes into account seasonal water-yield forecasts at some time during the year.

Operational applications of rate of runoff forecasting have been made in connection with the utmost possible employment of water at the time that an irrigation reservoir is full so that the diurnal fluctuation which could not otherwise be accommodated in storage might be used by drawing down the reservoir on a daily schedule in anticipation of the forecast volume from a given day's snowmelt contribution to runoff. Rate of runoff forecasting is also used in connection with flood control operations and under special conditions of utilization of natural flows for hydroelectric power generation.

Since practically all of the usable volumes of seasonal water yield which are impounded in irrigation and multiple-purpose reservoirs and used by diversion projects come from the high mountains, most of which are contained within national forests or other governmentally-owned areas, managing water-yielding drainage basins is of interest not only to the foresters but also to all users of the water. Practically all of the methods using forecasts of runoff from snowmelt are predicated on the continued existence of a uniform forest cover and on a recognizable amount of snow accumulation, with the assumption inherent in this system that whatever changes may take place in the management of the vegetal cover would be of no significance in changing the correlations upon which the forecasts are based.

These cooperative snow investigations are of particular interest to foresters in that through the various methods of harvesting timber, the climatic factors, such as temperature, wind, humidity, and incidence of solar radiation, may be so altered as to affect the rate of snowmelt and the daily discharge of mountain streams.

When large areas of a particular watershed are altered by means of the harvesting of timber, the interaction of the various factors used in forecasting water yields will be altered. This, in turn, will affect streamflow forecasts to an extent as yet unknown.

Such changes take place not only as a result of timber harvesting but also because of fire and of insect depredations. Where these changes occur on a mountain watershed with soils shallow in depth, considerable erosion and lowered quality of the increased streamflow might result from the accelerated daily melting of snows.

It is important for foresters to recognize that any alteration in the vegetal cover of high mountain forested watersheds results in a change in the rate of daily snowmelt and possibly of the volumes of water yielded from the snow pack. The extent and magnitude of these changes in streamflow may be harmful or beneficial in terms of seasonal water yield, and of rates of runoff. Since the harvesting of timber affects both the amount of snow accumulated over the winter and the discharge of streams, it would appear that more emphasis on the management of forests for water yield should be placed on the more stable, north-facing slopes in the mountains.

This investigation also points to the fact that the snow remaining in the mountain watersheds after the peak of spring flow has been reached contributes decreasing amounts day by day to the streamflow. When contrasting the amount of snow stored in open stands of timber with that stored in dense stands, one finds that the rate of snowmelt is greater, and the snow cover disappears more quickly in the open areas, particularly after the peak of the streamflow is reached for a given melt season. Comparisons also indicate that timber harvesting might be expected to make major changes in the volumes of water to be yielded from the melting of accumulated snow.

The Forest Service, in the light of these watershed management considerations, organized the Fraser Experimental Forest in 1938 and initiated investigations relating to the effect of timber cutting on water available for streamflow, years before this cooperative snow investigation between the Bureau of Reclamation and the Forest Service began. The existence of the Fraser Experimental Forest, together with its backlog of accumulated information on both the forest management and the hydrology of the drainage basin

made it an ideal location for the execution of the cooperative snow investigations. Publications dealing with forest investigations conducted at the Fraser Experimental Forest have been issued by the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Utilization of the Concepts Developed

Three progress reports on these cooperative snow investigations have been released (see References 84, 85, and 86). As these reports were released, immediate application was made of the techniques and ideas emanating from this cooperative investigation. One of the first and most widely used concepts is that of improving the accuracy of late summer, fall, and winter water-yield forecasts through the application of the recession concept following a recognition of the peak of the snowmelt hydrograph. This forecast is especially valuable in connection with hydroelectric energy generation, since it yields a very conservative predicted volume of inflowing residue of the given season's snowmelt contributions to the annual water yield.

Any precipitation which may yield runoff in the drainage basin will be in addition to the volume forecast by the recession method and, thus, can be readily introduced into operational considerations. During periods of little or no precipitation, such as occurred in parts of the West in 1954, residual forecasts by the recession method were found in numerous instances to be surprisingly accurate even though the volume of flow that they indicated appeared to be very low in comparison with the records of previous years in which there had been ameliorating contributions from summer rain.

Using the recession concept, Garstka [41] developed a procedure for forecasting the inflow to Shasta Reservoir after the seasonal peak had been recognized, which was found to work well even though it was applied in terms of the variable recessions of water resulting from rainfall rather than from snowmelt.

The method of analysis of a streamflow hydrograph, described in detail in section 8 of this report, was applied in an investigation of the effects of reforestation on streamflow by Garstka [40] in connection with the Geological Survey's continuation of investigations into the effect of reforestation performed in 1932 upon abandoned agricultural lands in central New York State.

Inasmuch as the preliminary results of the Fraser Experimental Forest Snow Investigations substantiated the recession concept, the use of maximum temperature as an index of snowmelt, and the verification of Light's equation, these concepts have been used in many design flood studies as described by Grout [48]. The "hydrothermogram" procedure described by Riesbol [79] is also based on the recession concept and the use of maximum temperature. Hydrothermograms were used in the inflow design flood studies for such dam sites as Clark Canyon Dam site in the Jefferson River Basin and Alpine Dam site in the Snake River Basin. Light's equation has been used in the rain-on-snow analysis prepared in the inflow design flood study for such dam sites as Stampede Dam site in the Truckee River Basin, Trinity Dam site in the Trinity River Basin, and Auburn Dam site in the American River Basin.

SECTION 2—REVIEW OF PREVIOUS WORK

Hydrologists, foresters, and meteorologists have been interested for a long time in the influence of the forest on snow. The unusual character of winter season runoff and the nature of the flows resulting from melting snow were recognized in one of the most exhaustive drainage basin experiments conducted in recent times, the so-called "Swiss Emmenthal" investigations reported by Engler [36]. The Emmenthal experiment was conducted during the period 1903–17 by the National Research Institute of Switzerland.

The first of the large-scale drainage basin experiments in the United States was begun by the Forest Service in 1909 with the selection of sites near Wagonwheel Gap in the headwaters of the Rio Grande in the high altitude Rocky Mountains of Colorado. This investigation was conducted through 1926 and is reported by Bates and Henry [11] [12]. Both the Emmenthal experiment in Switzerland and the Wagonwheel Gap experiment in the United States dealt with the effect of forest cover on seasonal and annual water yield rather than on flood-season flows or upon the processes of snowmelt.

Among the intensive investigations dealing specifically with the processes by which an accumulated snow pack turns into water flowing in the stream channel is the one described by Garstka [38]. This investigation was begun in 1940 on 2 cultivated and 1 forested drainage basin near East Lansing, Mich. Prior to this investigation, little work had been done on the relationship of various factors influencing the rate of snowmelt and the disposition of the water equivalent of the snow from natural drainage basins in contrast to small-scale, artificially bounded plot studies or laboratory-type experiments. Detailed discussions of the physical characteristics of snow and ice are given by Dobrowolski [33], Dorsey [34], and Barnes [9].

Numerous investigators have discussed the processes of snowmelt, using data of a climatological and hydrologic nature as available in published records. Church [22] [23] presents a comprehensive discussion of the melting of snow, snow surveying, and the forecasting of streamflow based upon snow surveys. Wilson [103] discusses the factors relating to the melting of snow, and in Reference 102 he discusses the thermodynamics of snowmelt.

The climatic factors of temperature, humidity, wind, and evaporation were measured in connection with the Wagon Wheel Gap experiment [11] [12]. These factors, however, were not analyzed in relation to daily snowmelt and streamflow from the two experimental watersheds. The climatic factors were used mainly to describe the conditions existing on the two watersheds before and after treatment.

A comprehensive discussion of the influence of forest cover on incident solar radiation, temperature, wind, humidity, and evaporation are described by Kittredge [60] [61] and Geiger [45]. Both of these authors point out the differences which exist in the climatic factors when a forest canopy is dense, when it is thin, and when it is totally removed. Neither of the authors, however, attempted to relate temperature, humidity, wind, and other factors to a daily rate of the melting of snow or of spring stream discharge.

In the broad forest management investigations currently being conducted at the Fraser Experimental Forest, it is important to recognize the contribution which various investigators made concerning the relationship between the density of forest cover and the accumulation of snow.

Church [21], in reporting upon the observations at Mount Rose Observatory for the period 1906–12, was among the first to recognize the importance of the forest canopy upon the conservation of snow. His observations on this subject can best be expressed by a direct quotation: [3]

> The action of unbroken forests upon the snow is unlike that of timber screens, particularly on the lower slopes where the wind is less violent. These forests catch the falling snow directly in proportion to their openness, but conserve it, after it has fallen, directly in proportion to their density. This phenomenon is due to the crowns of

[3] Reference 21, page 799.

the trees, which catch the falling snow and expose it to rapid evaporation in the air, but likewise shut out the sun and the wind from the snow that has succeeded in passing through the forest crowns to the ground.

The most efficient forest, therefore, from the point of view of conservation, is the one that conserves the largest amount of snow to the latest possible time in the spring. This has been found by measurement to be the forest with the maximum number of glades, which serve as storage pits into which the snow can readily fall, but the wind and the sun cannot easily follow. One such forest was found to have conserved, at the close of the season of melting, 3½ times as much snow as a very dense forest adjacent to it.

The management of the water-yielding drainage basins is of direct interest not only to the Forest Service responsible for the maintenance of the drainage basin, but also to the Bureau of Reclamation and all of the numerous interests which utilize the water resources. Connaughton [26], in 1935, carried on a 3-year study of snow accumulation and melt as affected by forest cover in ponderosa pine lands in southern Idaho.

For the purpose of finding out how timber cutting might affect the water yield from the snow, five study plots were located on level ground within a radius of ½ mile. The plots included a denuded area beyond the zone of influence of any vegetation, which served as a control, and one plot each in sagebrush, young timber, virgin timber with no reproduction beneath the trees, and virgin timber with a dense stand of reproduction. The quantity of snow accumulated during the winter was very nearly the same in the denuded and sagebrush plots, but was 5 percent less in the reproduction or young timber plots, 25 percent less in the forest lacking reproduction, and 30 percent less in the forest containing reproduction. These differences were attributed to interception and evaporation of snow on the tree crowns.

Connaughton found that snowmelt was affected by the cover conditions. The snow melted evenly both in the open and in the sagebrush plots. It melted in a spotty pattern under the timber. It was concluded that the retardation of the rate of snow melting by forest cover is one valuable means of increasing duration of runoff and distributing the peak flow of rivers over a considerably longer period of time. Connaughton drew this conclusion from the fact that a dense stand of virgin ponderosa pine could retain from 14 to 20 percent of the winter's accumulation of water at the time that snow melting was complete on the adjacent denuded areas.

This study was followed by another, Haupt [52] in the same area but on steep slopes more typical of the ponderosa pine lands. Haupt's study dealt with slope aspects and cover conditions. Aspects were segregated in cardinal directions, and cover conditions were defined as mature stand, full stand, sapling stand, small brush openings, and large brush openings. The best opportunity for maximum snow storage and retention existed in older-growth ponderosa pine on north slopes. On such aspects, Haupt concluded that the greatest storage and retention effects would be obtained by creating large openings in the forest stand. Haupt observed that large openings should be avoided on sunnier aspects, such as south slopes. North slopes were more effective for accumulating snow during the winter period and retaining it during the spring. These differences are believed to be attributable to slower melting in the early winter and spring on steep slopes where the sun's rays strike more obliquely and where topographic shading is more prevalent.

The Fraser Experimental Forest is the site of a more complete study of the effect of timber harvesting on water available for streamflow. A progress report on this study is given by Wilm and Dunford [101]. This study is continuing at the Fraser Experimental Forest. This progress report dealt with a group of twenty 5-acre plots in a forest of mature lodgepole pine. Sixteen of the plots were cut over by selective cutting methods. When the various components of net snow storage and rainfall were combined with estimates of snow evaporation and the data on soil moisture deficits, quantitative figures on the amount of water available for streamflow under each timber-cutting treatment were obtained. On the uncut plots, this amount was 10.34 inches, or about 42 percent of the total annual precipitation. The heavily cutover plots yielded 13.52 inches, so that this treatment actually caused an increase of 31 percent in the quantity of snow-water equivalent available for streamflow. Contrary to other studies, there was no measurable difference in the length of the snowmelt period between several treatments. Apparently, the greater depth of snow that accumulated in the cutover areas compensated for a more rapid melt. This study was followed by another dealing with the effect upon the quantity of water available for streamflow by thinning a young stand of lodgepole in the Fraser Experimental Forest. Goodell [47] concluded that decreasing the dens-

ity of a young stand of lodgepole would result in an increase in the water available for streamflow by about 20 percent, and that all, or nearly all, of the increase was the result of decreased interception loss of snow.

Plot studies at the Fraser Experimental Forest dealing with the effect of harvesting timber on water available for streamflow and on snow accumulation have shown consistently that these may be increased, as reported by Love [66]. The results of a depredation of pine and spruce by bark beetles in the White River Drainage Basin in Colorado presented an opportunity to ascertain, on a large scale, what the effects of thinning of stands might be. This study by Love [67] dealt with an area of 226 square miles in the 762-square-mile White River Drainage Basin in which bark beetles had killed the Engelman spruce and the lodgepole pine. As a result of the death of these trees, more snow accumulated in the timberlands and resulted in about a 22-percent increase in streamflow at the main gaging station near Meeker, Colo. Water drainage from the basin was obviously different after the death of the pine and spruce. The effect of the death of the pine and spruce was similar to that of harvesting or thinning mature stands, with the exception that the defoliated trees remained on the area. The rate of snowmelt was observed by Love to have changed, with the months of highest flow shifting from May to June. This indicates that the interaction of the various climatological factors of temperature, humidity, wind, and solar radiation had been so modified by the death of the trees that the snowmelt conversion to streamflow was changed in its character and also in the volume of streamflow yield.

In the central Sierra Nevada, Kittredge's [61] studies of influence of forest on snow accumulation in the ponderosa-sugarpine-fir zone indicated that the forest canopy held from 13 to 27 percent of the year's snowfall off the ground. The lowest interception loss was found in the least dense stands. Evaporation loss from the snow pack was quite small. Openings left in the forest by cutting accumulated more snow than did much larger openings in the meadows. The rate of snow-melt was not affected much by the type of cutting or cover.

Observations from the experience in investigations of this nature can be summarized as follows: Forest cover serves both to withhold snow from the ground and to reduce the rate at which water is released from the snow pack. A forest canopy can have both adverse and beneficial effects upon the volume of water yielded. Interception by the tree canopy reduces the winter accumulation of snow, whereas, on the other hand, shading of the snow surface and protection from the wind tend to reduce evaporation losses from the snow pack.

Opening a forest canopy permits more snow to reach the ground, but it also speeds its disappearance, resulting in the prospect of increased rate of conversion of the snow pack to streamflow. This is likely to occur especially during periods when the peak of the snowmelt season is about to be attained.

Another intensive snow investigation program (in which the Bureau of Reclamation participated to a limited extent and portions of which are continuing under the guidance of the Forest Service) was that of the Corps of Engineers and the Weather Bureau. These cooperative investigations were conducted principally at three field laboratories: the Central Sierra Snow Laboratory near Soda Springs, Calif.; the Upper Columbia Snow Laboratory near Marias Pass, Mont.; and the Willamette Basin Snow Laboratory, Blue River, Oreg. Analytical work was performed at the Processing and Analysis Unit, originally maintained at San Francisco and Oakland, Calif. and later transferred to Portland, Oreg. This extensive cooperative program was initiated in 1944 and completed in 1956. A comprehensive report entitled "Snow Hydrology" [88] describes these investigations, the objectives of which were, in general, parallel to those of the cooperative snow investigations conducted at the Fraser Experimental Forest which are the subject of this report.

The above review of previous work on the literature deals, in general terms, with the broad subject of drainage basin and watershed investigations in relation to snow accumulation, snow melting, and resulting streamflow. Additional references will be given in the following chapters dealing with specific phases of the broad snow investigations.

The following references deal with certain specific aspects of the cooperative snow investigations which are the subject of this report: Brown and Dunford [17]; Riesbol [79]; Peasley, Garstka, and Goodell [77]; Bertle, Dunford, and

Garstka [15]; Garstka, Bertle, and Dunford [43]; Garstka [42]. Three progress reports were processed in a limited number, describing these snow investigations: Report No. 1 [84] deals with the 1948 snowmelt season; Report No. 2 [85] deals with the 1949 snowmelt season and includes a section on instruments; and Report No. 3 [86] deals with the 1950 snowmelt season.

SECTION 3—DESCRIPTION OF THE FRASER EXPERIMENTAL FOREST

A. General

The general features of the Fraser Experimental Forest are shown in figure 1. Topographic features and location of the measuring stations are shown in figure 2. The experimental forest lies 65 miles west and north of Denver, Colo. Totaling 36 square miles, it is representative of the land of the Continental Divide. Occupying the headwaters of St. Louis Creek, a tributary of the Fraser River, which, in turn, is an important tributary of the Colorado River, it is typical of the high-altitude lodgepole pine and spruce-fir forests of the Rocky Mountains.

B. Climate and water yield

The climate is cool, with an average yearly temperature of about 35° F. The mean monthly temperature for January is 15°; for July 55°. At the Fraser Experimental Forest Headquarters, the annual precipitation averages about 24 inches, of which two-thirds occurs as snowfall. Yearly precipitation has varied from 15 to 30 inches. Figure 3 shows the monthly distribution of precipitation and temperature for three years when wintertime observations were made within the forest.

Water yield from the forested watersheds amounts to 45 to 55 percent of the annual precipitation or from 1 to 1½ acre-feet per acre. About 70 percent of this yield comes from melting snow during April, May, and June each year. Only 5 percent comes directly from summer rain and the remaining 25 percent from the stable perennial base flow. Since, however, even the base flow must be derived largely though indirectly from snow, it may be concluded that about 90 to 95 percent of the total annual yield comes from snow.

C. Topography

The topography of the Fraser Experimental Forest is typical of the Southern Rocky Mountain province. On the west side of the forest occur narrow, steep-sided valleys and rugged mountains, while on the south and east sides are found remnants of an old peneplain, nearly level in extent but dissected along its sides by mountain glaciers (figures 4 and 5). The elevation ranges from 9,000 to nearly 13,000 feet. Area-elevation relationship for St. Louis Creek, which has a drainage area of 32.8 square miles, is shown on figure 6.

The streams within the experimental forest have a coarse pattern. Generally, they are far apart and are not deeply entrenched. In places, the stream channels are poorly defined, often disappearing beneath the surface trash and litter. This condition is especially prevalent at higher altitudes, especially in the spruce zone. Gullies as determined by down-cutting beds and raw stream banks are rare. A few raw-sided drainageways are prevalent in the upper headwaters of the many streams. These have the general appearance of having originated as a result of snowslides in the upper spruce and alpine zones. They appear to be a part of the normal geologic cycle.

Many of the side streams originate as springs or in areas of a series of springs high up on the slopes of the drainages. Often such springs originate only a few hundred feet below the borders or ridge tops of the drainageways. The origin of the springs has several explanations. However, the most logical seems to be that relatively impervious bedrocks interfere with the normal downward movement of seepage water, forcing such waters to the surface. Springs tend to concentrate in certain localities and apparently have been active over long periods, because such localities show evidence of land slides with resulting depressions and small bogs. Springs are prevalent on both sides of the main St. Louis Creek. They contribute greatly to the sustained summer flow and are often found at the base of large glacial till deposits, and are nearly always accompanied by marshy, wet areas and by small peat bogs.

D. Geology and soils

Biotite schist, and gneiss are the dominant rocks on the experimental forest. They are bro-

Figure 1. Byers Peak, elevation 12,790 feet above sea level. This is a general view of the Fraser Experimental Forest. The town of Fraser is off the right hand edge in the meadow visible in the center. The windtower and other installations are in a valley beyond the second ridge along the right-hand edge as counted from the meadow. (Photo copyright by Sanborn Souvenir Co., Denver. Reproduced by permission.)

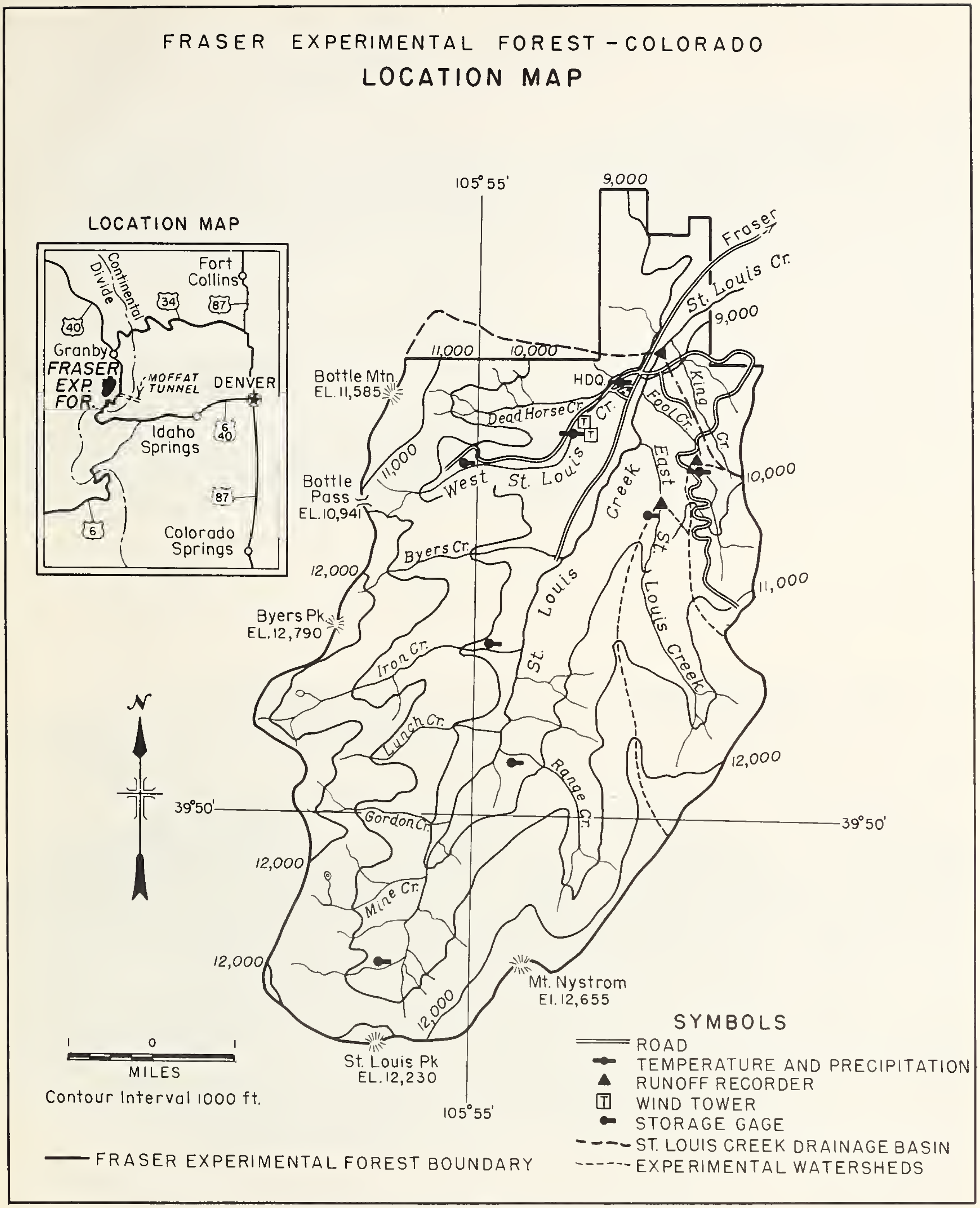


Figure 2. Map of Fraser Experimental Forest.

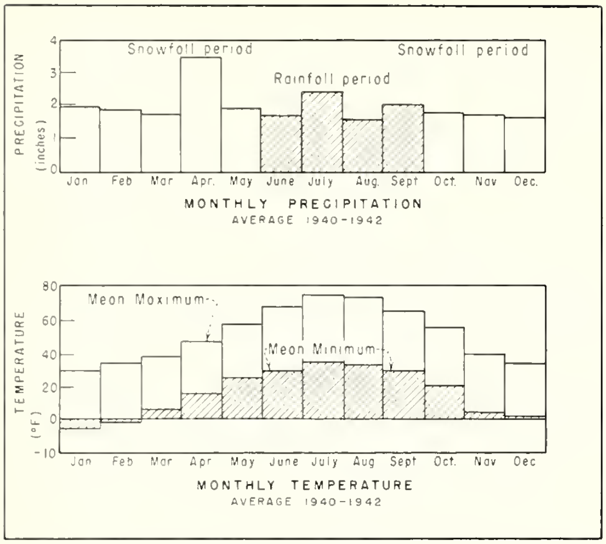


Figure 3. Mean monthly precipitation and temperature within the Fraser Experimental Forest.

ken and twisted and deeply fractured in many places. Occasionally, small areas of granite occur, suggesting that the original bedrock was granite and was later metamorphosed. These granitic rocks often form small protruding ridges and weather slower than the adjacent schist. The bedrock has been considerably altered by glaciation. Talus accumulations are found along the slopes of the mountain peaks. Landslides have occurred throughout the forest and appear to have been developed during periods of excessive moisture, perhaps following fires when the landscape was denuded of vegetative cover. In some places, the natural slopes are simply too steep to prevent soil movement when the mass is thoroughly saturated, as might occur during the spring snowmelt period. Glaciers have been active throughout most of the watershed. In many places, terminal moraines can be found as well as large areas of glacial till and outwash. The glaciers altered the topography and deepened the valleys so that they are now V-shaped. The flood plains are composed of cobbles and gravelly materials which are capable of carrying a great deal of underground seepage to the main stream channel. Above timberline, cirques are found at the base of the high mountain peaks.

Soils from the schist and gneiss occur on the steep mountain slopes under a cover of trees or alpine turf. They are rocky, generally acid, have varying depths and are adapted to the rapid movement of water. Little erosion occurs. Figure 7 shows the extent of the various soil classes

Figure 4. Rugged mountains characterize the west side of the Fraser Experimental Forest.

Figure 5. Remnant of an old peneplain covered with alpine turf on the south and east sides of the Fraser Experimental Forest.

which are grouped according to their geologic origin.

There follows a brief description of the major soil groups:

1. *Schist and gneiss soils under alpine cover.* These soils have a cover of grass and sedge typical of the alpine region. At their lower extreme, where drainage tends to concentrate, willow fields occur. The surface commonly contains many exposed rocks. The surface soil consists of a 3- to 5-inch layer of black, gritty loam. This layer is high in organic matter and is densely matted with roots. Beneath this surface layer occurs a brown, gravelly layer extending to depths of 12 to 15 inches. Below this layer, the C horizon consists of only loose rocks and gravel.

2. *Soils on schist and gneiss under forest cover.* These soils are divided into two broad groups—those occurring under lodgepole pine and those occurring under spruce-fir. The soils under lodgepole pine are found at lower elevations and on dry sites at higher elevations. They are protected by a layer of litter ranging in thickness from a trace to about 2 inches. Immediately beneath the surface litter is a thin, gray, acid layer. When moist, it is hard to differentiate, but when dry its grayness and powdery, dusty nature separates it distinctly from both the horizons above and below.

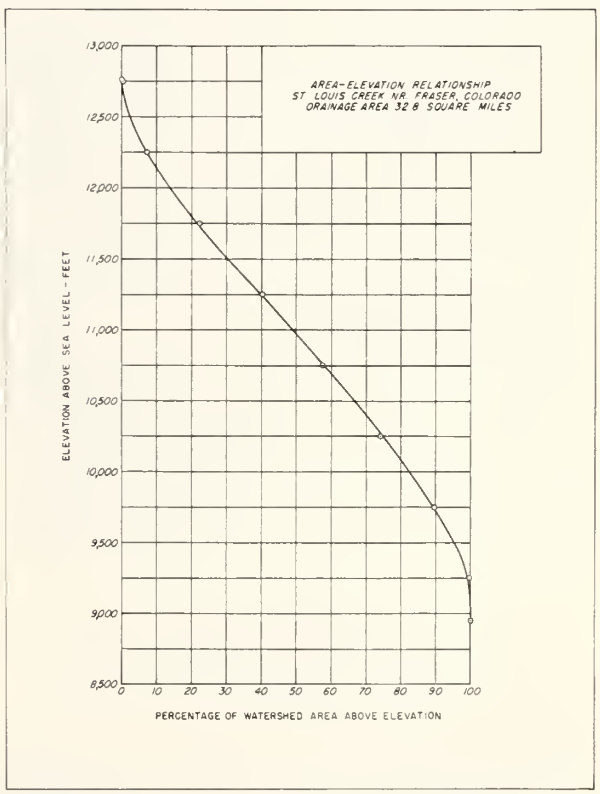


Figure 6. Area-elevation relationship for St. Louis Creek near Fraser, Colo.

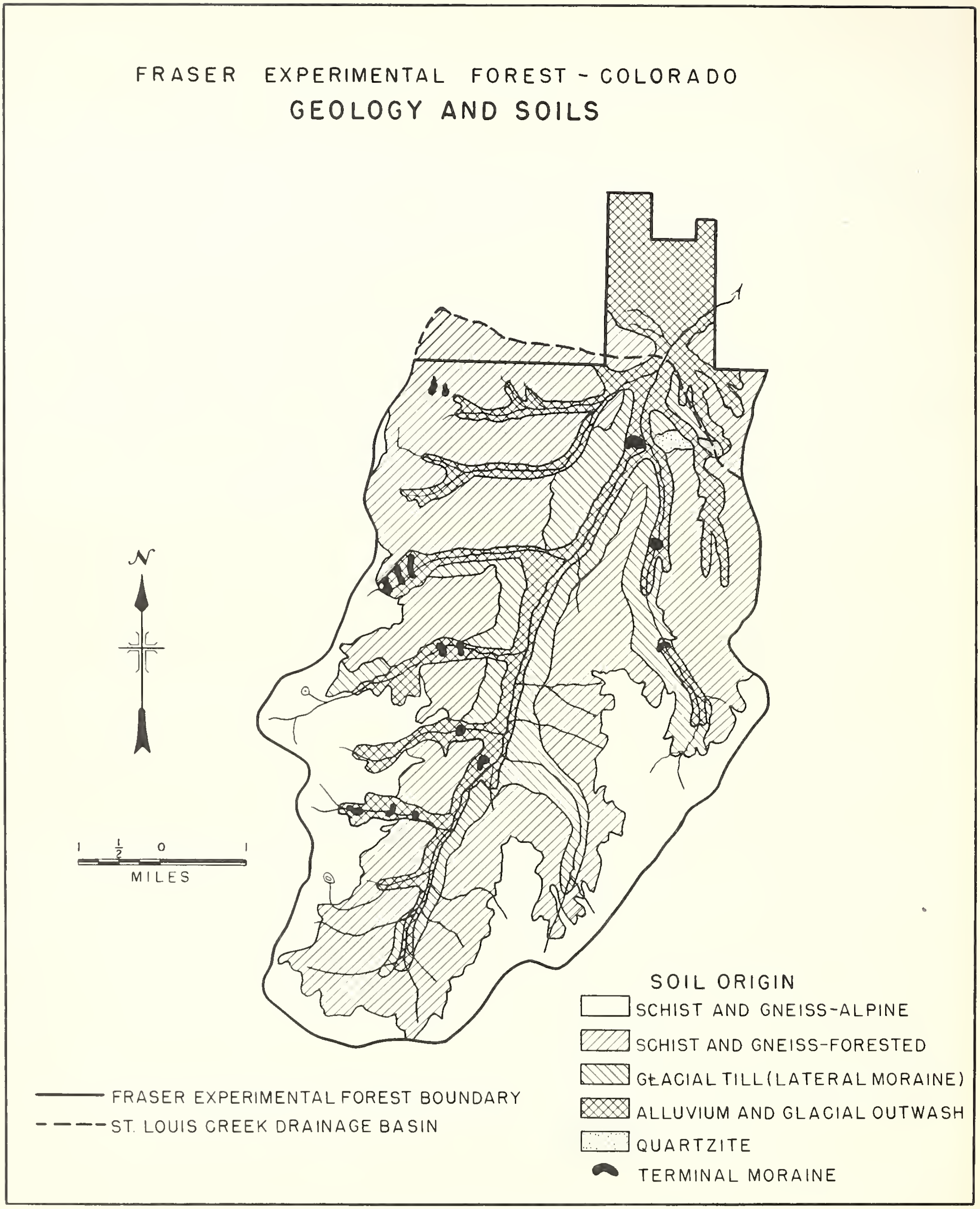


Figure 7. Map showing the geologic origin of the soil.

This gray layer is rarely more than 3 inches thick. Immediately below the gray A_2 horizon occurs the brown B horizon which grades into the parent material. This brown layer ranges in thickness from 4 to 8 inches. The C horizon consists of angular fragments of gravel with little fine material, or it may be composed of disintegrated biotite schist.

The soils developed under the spruce are well protected by a dense litter layer consisting of moss, lichen, and dead twigs and needles. Immediately below the dense moss litter occurs a light gray, dusty, bleached layer 2 to 4 inches thick. This layer is very prominent when dry. Beneath this horizon occurs a light, yellowish brown layer, ranging in thickness from 8 to 15 inches. This light brown layer is especially characteristic of the spruce soil. Both these horizons are acid. The C horizon is usually very coarse in texture and may consist of rotted schist rock or coarse, angular gravel.

3. *Glacial till soil.* The soils developed from glacial till have the same characteristics as described previously for those under lodgepole pine and those under spruce-fir. The soils are differentiated because of the character in the parent material which consists of cobbles and coarse gravels to considerable depths. These soils are highly permeable and allow water to move freely through them.

4. *Soils on alluvium and glacial outwash.* Soils on alluvium and glacial outwash are often covered by spruce. These flood plains are relatively level in cross section. Their grade is represented by a series of relatively level areas separated by steep steps or breaks. The parent material consists of cobbles and gravels to great depths. The surface litter is thick and very spongy. Numerous bogs and seeps occur along the sides of the streams. The soil profile is much less consistent or uniform than that of the upland. Soils on the glacial outwash and alluvial areas are primarily products of excessive moisture and because of the vegetation and litter produced, serve well to retard excessive runoff and to hold the present stream channels in place.

5. *Soils derived from quartzite.* Soils derived from quartzite are extremely limited in extent. They are mainly covered with lodgepole pine and have the same general characteristics as described for the soils derived from schist and gneiss covered with lodgepole pine. These quartzite soils exhibit a more pronounced gray layer than was found in the other soils.

E. Native vegetation

The native vegetation occurring on the experimental forest is typical of the Continental Divide zone of the southern Rocky Mountains. Lodgepole pine (Pinus contorta, Dougl.), Engelmann spruce (Picea engelmannii, Parry), and subalpine fir (Abies lasiocarpa (Hook) Nutt.) are the important tree species. Virgin stands are commonly 200 to 400 years old. Scattered patches of quaking aspen (Populus tremuloides, Mich.) occur in areas opened by fire, snowslides, and logging. The forest floor is covered with a thick layer of litter and often a dense mat of grouse whortleberry (Vaccinium scoparium, Leiberg). Young pine, spruce, and fir, along with scattered aspen and buffalo berries (Lepargyrea canadensis, (L) Nutt.), are often found beneath the forest canopy. Alpine areas consist of barren rock, intermixed with meadows containing grasses, sedges, weeds, and dwarf willow. Figure 8 shows the areal extent of the three main classes of native vegetation.

On the experimental forest, the lodgepole pine extends from the 9,000- to the 11,000-foot contours. It occurs just below and overlapping the spruce-fir type, which extends from about 10,000 feet to timberline at 11,500 to 12,000 feet. In general, the forest cover is mature lodgepole pine, intermixed with Engelmann spruce and alpine fir on the moist sites. This timber stand contains 300 to 400 trees per acre larger than 3½ inches in diameter. The trees range in size from about 4 inches in diameter to a maximum of 24 inches. The shortest trees average 35 feet in height and the tallest about 80 to 85 feet. A few valley bottom trees reach heights of 100 feet or more. The average volume is about 12,000 board feet per acre with a range from 8,000 to 17,000. Little herbaceous vegetation is to be found on the forest floor except along streambanks.

F. Streamflow

The interactions of the climatological and physical characteristics of the drainage basin are integrated in a characteristic distribution and shape of the annual hydrograph. The area of the drainage basin, confluent above the St. Louis Creek stream gaging station, is 32.8 square miles. The altitudinal range of the drainage basin is from about 8,980 feet to 12,790 feet above sea level. The

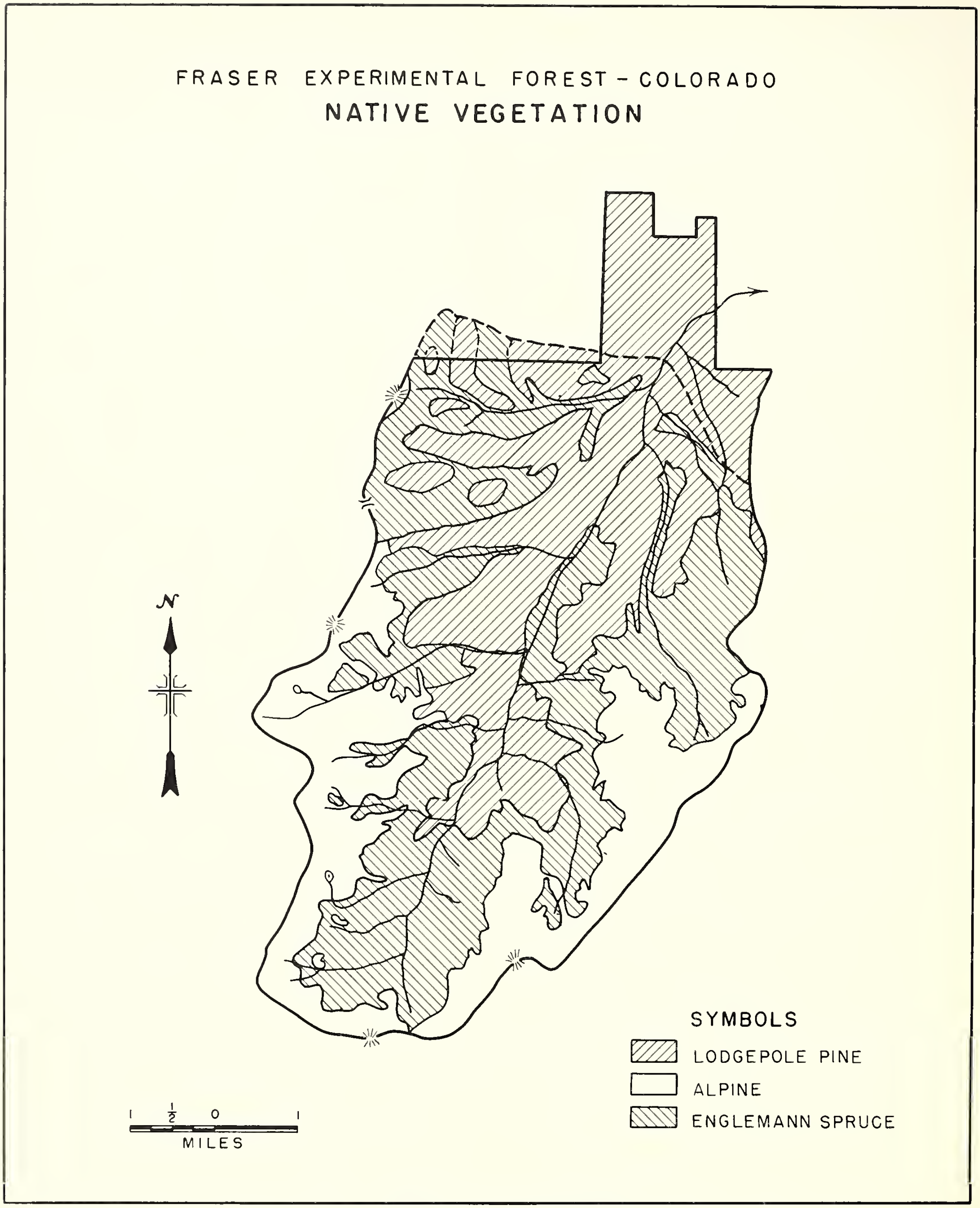


Figure 8. Native vegetation.

St. Louis Creek stream gaging station is maintained jointly by the office of the Colorado State Engineer and the Geological Survey, Department of the Interior. Runoff records from this station and precipitation data from the Weather Bureau cooperative station, maintained in the town of

HYDROGRAPHS

ST. LOUIS CREEK NEAR FRASER, COLORADO
AND
PRECIPITATION AT FRASER, COLORADO

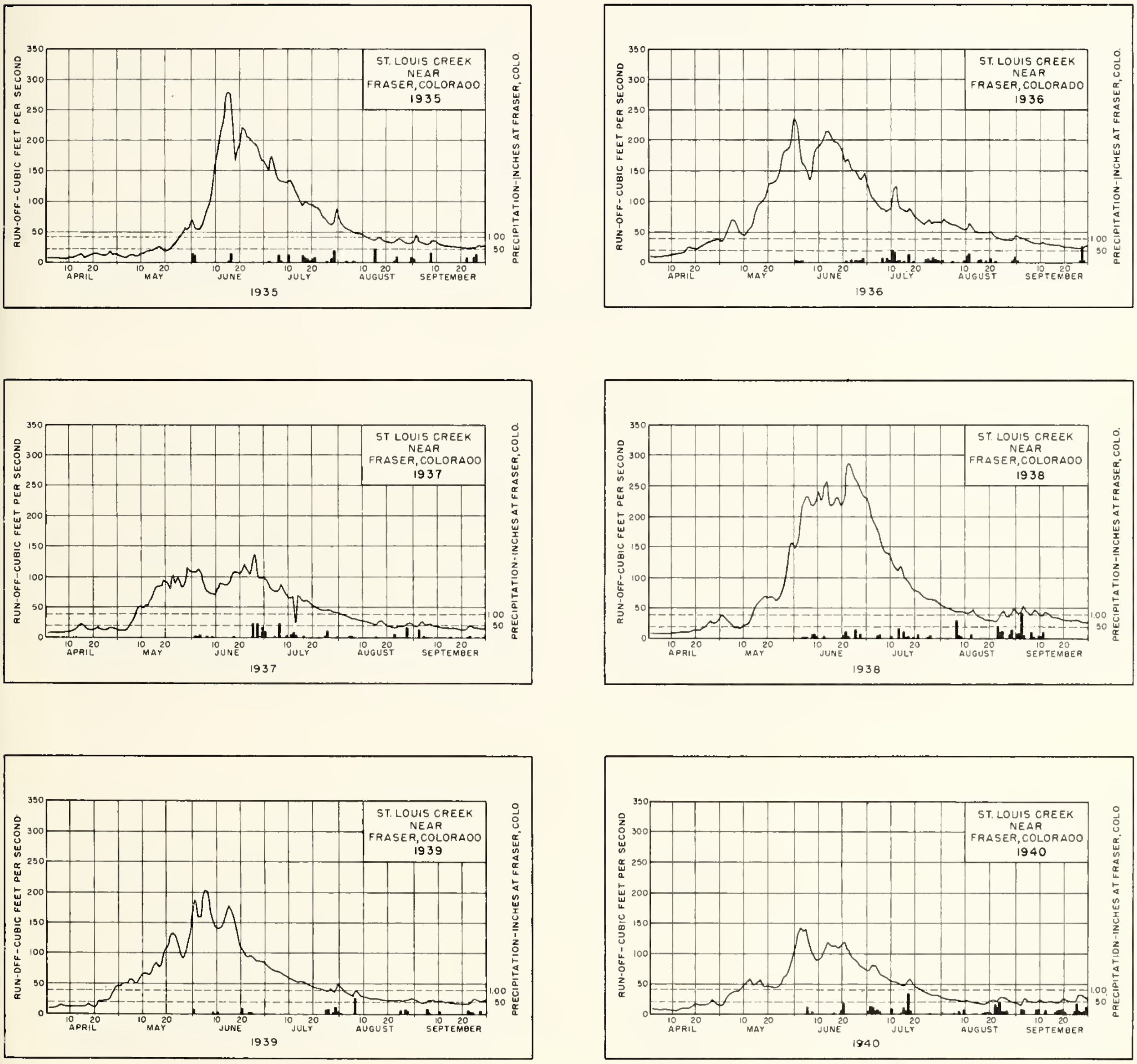


Figure 9. Streamflow and precipitation, St. Louis Creek, 1935 to 1940.

Fraser, Colo., are presented in figures 9, 10, 11, and 12.

The hydrographs for the period of intensive data gathering, 1948 through 1953, have been plotted as figure 13 to show the variation from year to year of the time of occurrence of the peak of the snowmelt hydrograph and the monthly distribution of the volumes of flow.

HYDROGRAPHS
ST. LOUIS CREEK NEAR FRASER, COLORADO AND PRECIPITATION AT FRASER, COLORADO

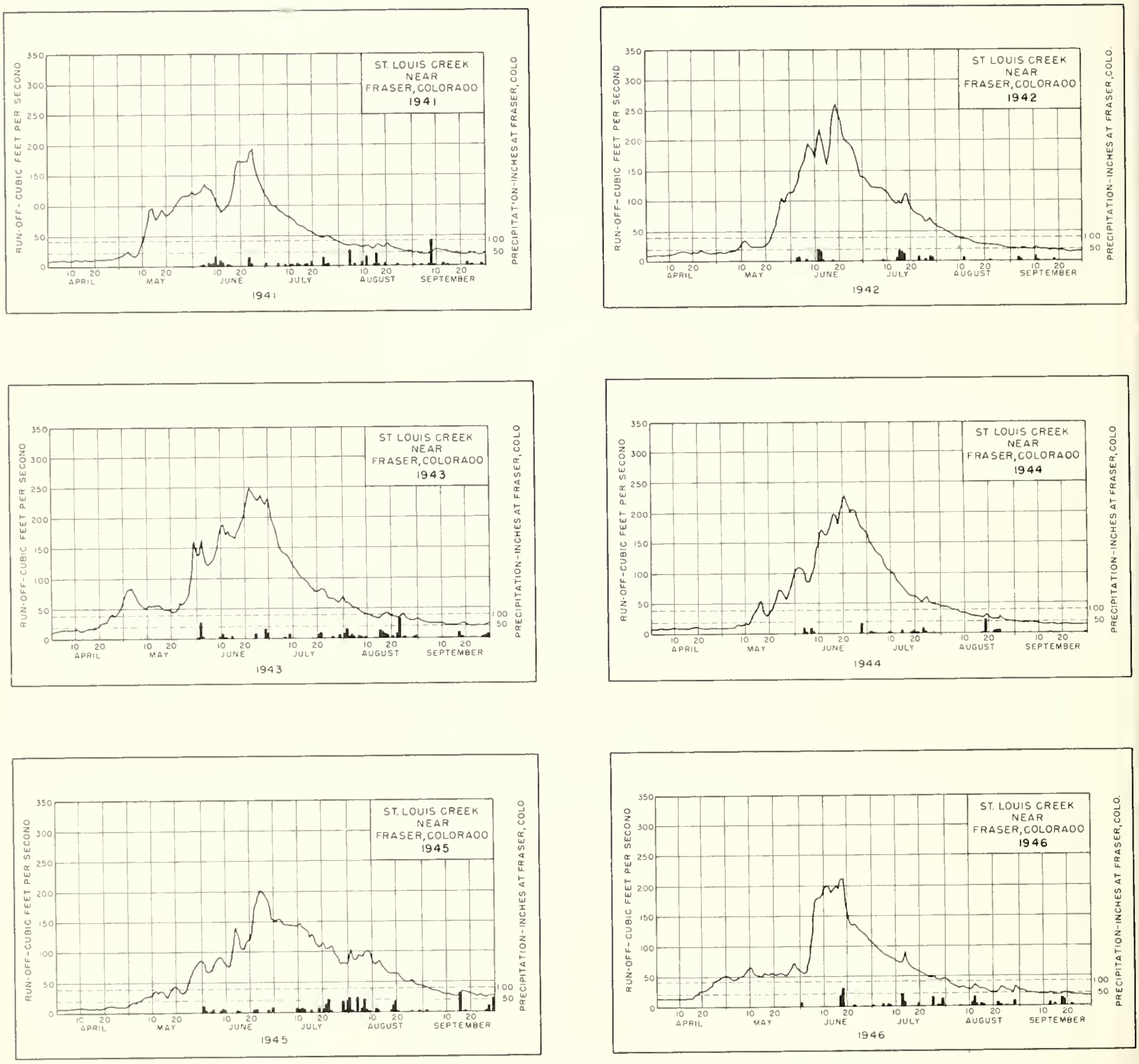


Figure 10. Streamflow and precipitation, St. Louis Creek, 1941 to 1946.

HYDROGRAPHS
ST LOUIS CREEK NEAR FRASER, COLORADO AND PRECIPITATION AT FRASER, COLORADO

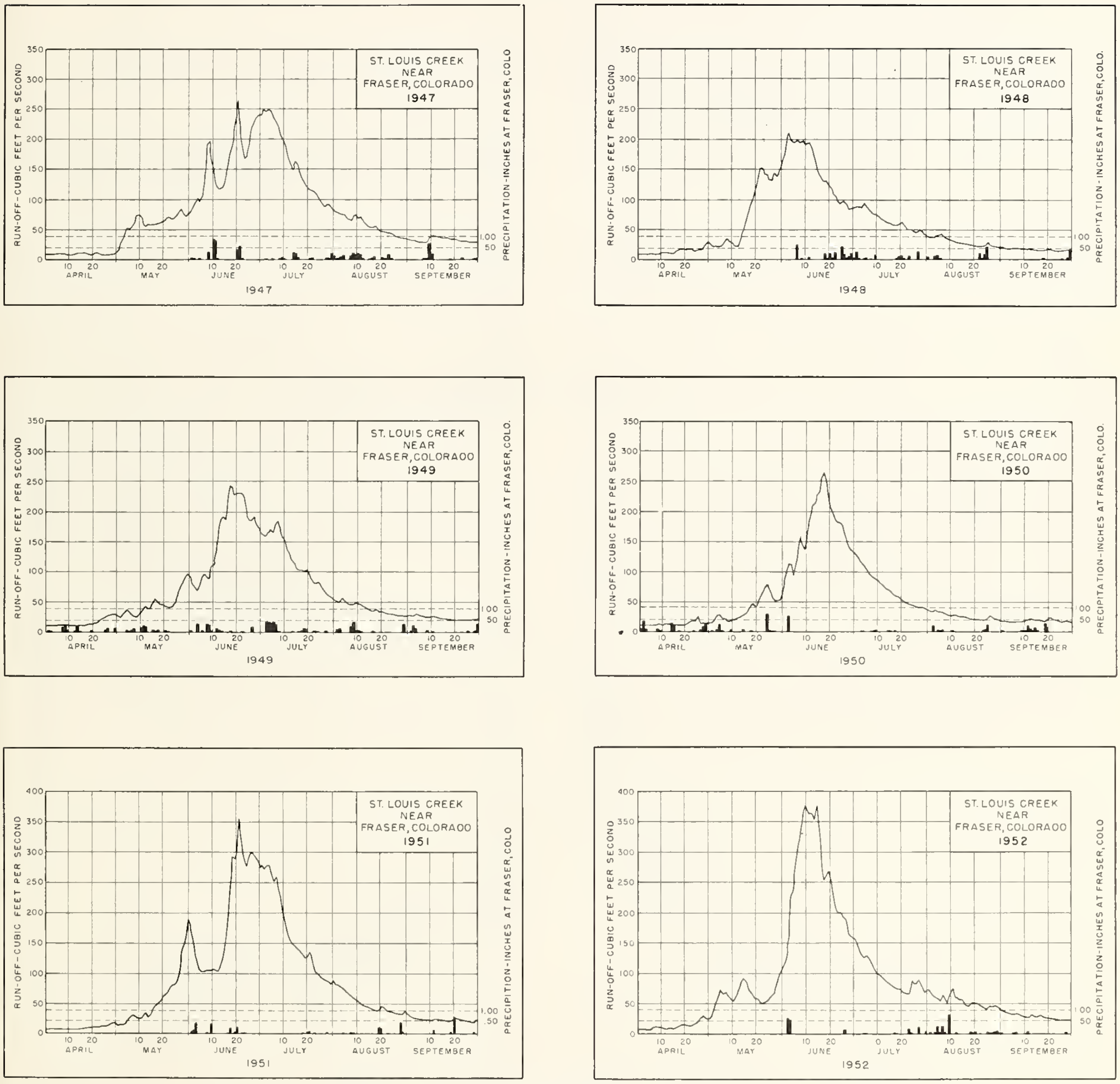


Figure 11. Streamflow and precipitation, St. Louis Creek, 1947 to 1952.

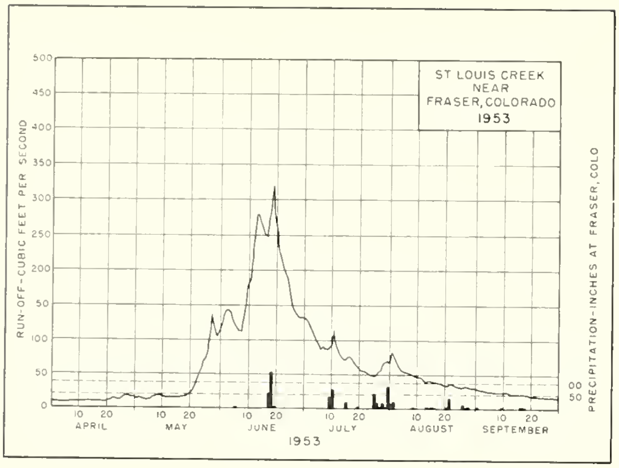
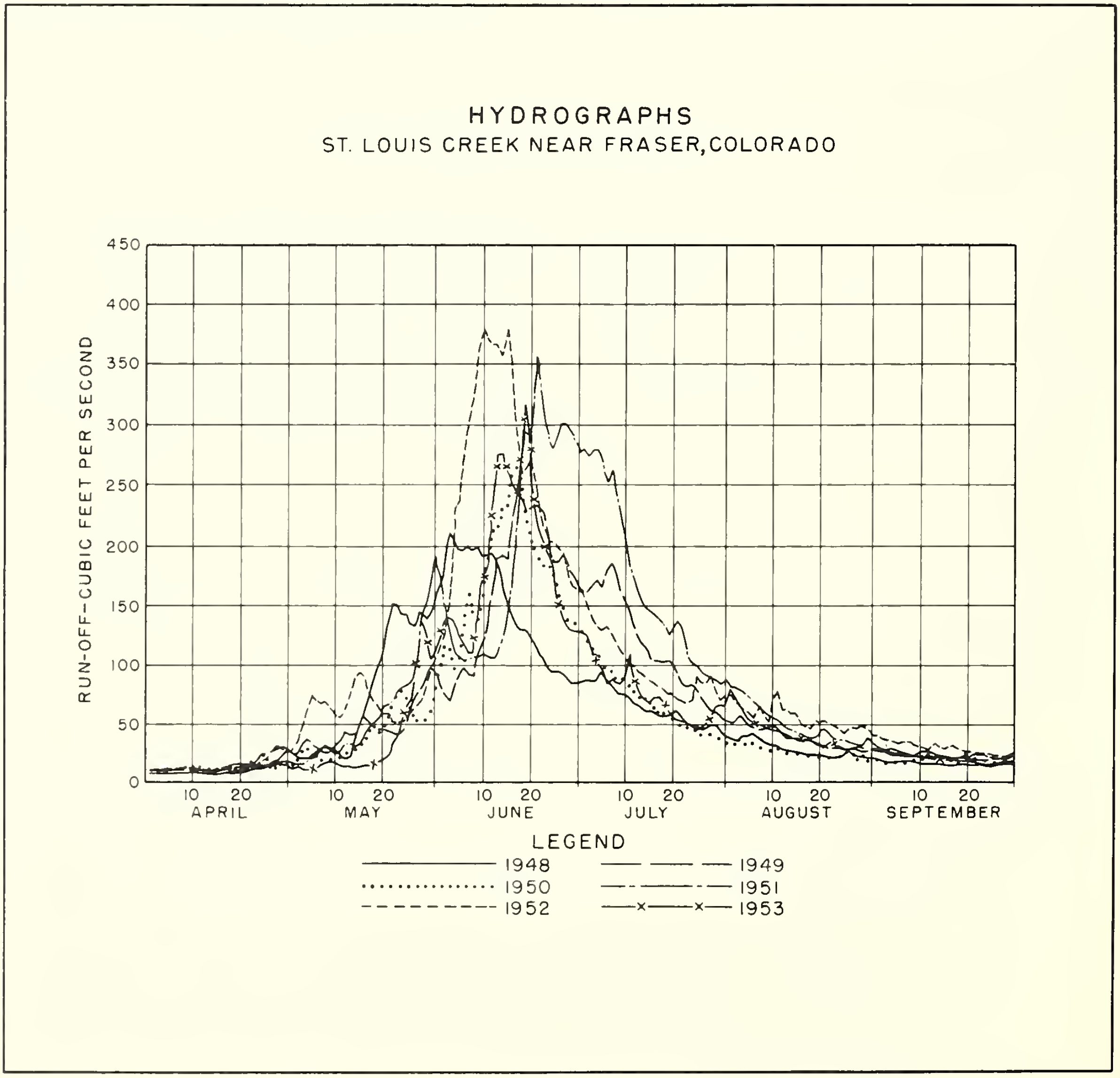


Figure 12. Streamflow and precipitation, St. Louis Creek, 1953.

Figure 13. Comparison of hydrographs for years 1948 to 1953, St. Louis Creek near Fraser, Colo.



SECTION 4—INTERPRETING THE COMMONLY AVAILABLE MAXIMUM AND MINIMUM TEMPERATURES IN TERMS OF DEGREE-DAYS

Air temperature is one of the most applicable indexes relating to snowmelt. Although the sun is the source of energy for the melting of snow, the exact manner in which solar radiation becomes available and active can be, at times, very intricate. Miller [71] concluded that, during the melting hours, most of the heat applied to the snow came from solar radiation, but that as much as 300 calories per square centimeter per day from the insolation went to heat the air. In view of the high albedo of a clean, freshly fallen snow surface, it is evident that the solar energy must be made available for snowmelt in forms other than by direct solar radiation. Miller [71] concluded that one important source of heat for snowmelt in the melting of the deep snow pack in the Sierra Nevada in California in 1946 was the heat relayed to the snow from the forest canopy and other local environmental features.

The amount of heat available from the air is indicated by the "degree-days" and the wind speed. Linsley, Kohler, and Paulhus [65] defined, on page 27, a degree-day as being a departure of 1° per day in the daily mean temperature from an adopted reference temperature. Many publications, especially those dealing with air conditioning and heating, refer to a degree-day, based upon departures from a temperature of 65° F. In hydrologic work, however, the degree-day is usually based upon departures from a 32° F base or some other temperature selected in such a way as to reflect a lapse rate correction aimed at describing the degree-days above 32° F operative in the zone actively subjected to snow melting.

Degree-days were used by Clyde [24] in his work dealing with snow-melting characteristics in Utah in 1931.

The average of the daily maximum and minimum temperatures is commonly used as a basis for computing the degree-days above 32°. However, in many parts of the West, the diurnal fluctuation of temperatures, especially the depression of the minimum, is so large as to yield average temperatures which oftentimes turn out to be below 32° F, indicating zero degree-days, whereas actually, during a part of the day, snowmelt conditions may have prevailed due to temperatures in the 50's.

One of the problems confronting the hydrologist is that of securing the most indicative interpretation of what meager temperature data are commonly available within, or near, the drainage basin under consideration. Long records of thermograph traces and hourly values of temperature are rare. In the overwhelming majority of cases, the practicing hydrologist is limited to daily maximum and minimum temperatures secured by a cooperative observer at a weather station, oftentimes some distance removed from the area under study. To aid the hydrologist in deriving the best estimate of degree-days from the daily maximum and minimum temperatures, the following studies were made.

Using the 1948 and 1949 Fraser Experimental Forest Headquarters Station data, comparisons were made between degree-days above 32° F, as computed from the hourly thermograph records, and the following:

a. The daily maximum temperature.

b. The average of the daily maximum and minimum temperature.

c. The average of the maximum and effective minimum temperatures. The effective minimum temperature is defined as the actual minimum that is equal to or above 32°, but if the actual minimum is below 32°, the effective minimum is considered to be 32° F.

These relations are shown on figures 14 to 19 and summarized in table 1. A comparison of figures 14 and 15 with figures 16 and 17 shows the superiority of maximum temperature alone as an index of degree-days above 32° as compared with the average of the daily maximum and minimum air temperatures. Figures 18 and 19 illustrate that the relation between degree-days and the average of the maximum and the effective mini-

Table 1—Summary of degree-day correlations for Fraser Experimental Forest Headquarters Station

Degree-days (Y) as computed from hourly values of hygrothermograph records in relation to (X) daily maximum temperature, average of maximum and minimum temperature, or average of maximum and effective minimum temperature, Fraser Experimental Forest Headquarters Station.

Year	Month	Comparison with maximum temperature			Comparison with average of maximum and minimum temperatures			Comparison with average of maximum and effective minimum temperature		
		Equation	$\bar{r}$	$\bar{S}$	Equation	$\bar{r}$	$\bar{S}$	Equation	$\bar{r}$	$\bar{S}$
1948	April	Y=0. 444X−15. 9	0. 981	0. 73	Y=0. 585X−13. 4	0. 938	1. 29	Y=0. 888X−30. 1	0. 981	0. 73
1949	do	Y=0. 422X−15. 1	0. 966	0. 78	Y=0. 351X− 6. 0	0. 734	2. 05	Y=0. 828X−28. 0	0. 957	1. 98
1948	May	Y=0. 532X−19. 5	0. 982	0. 94	Y=0. 742X−18. 9	0. 962	1. 36	Y=1. 064X−36. 5	0. 982	0. 94
1949	do	Y=0. 539X−20. 2	0. 960	1. 11	Y=0. 929X−28. 7	0. 893	1. 79	Y=0. 912X−30. 5	0. 901	1. 73
1948	June	Y=0. 545X−19. 2	0. 927	1. 72	Y=1. 218X−42. 4	0. 887	2. 12	Y=1. 188X−42. 1	0. 948	1. 46
1949	do	Y=0. 628X−24. 1	0. 963	1. 60	Y=1. 104X−37. 1	0. 939	2. 05	Y=1. 214X−43. 2	0. 957	1. 72
1948	April plus May plus June.	Y=0. 569X−21. 5	0. 966	1. 52	Y=0. 739X−19. 0	0. 939	2. 02	Y=1. 134X−39. 7	0. 975	1. 30
1949	do	Y=0. 606X−23. 5	0. 969	1. 53	Y=0. 663X−16. 6	0. 892	2. 81	Y=1. 126X−39. 5	0. 962	1. 70

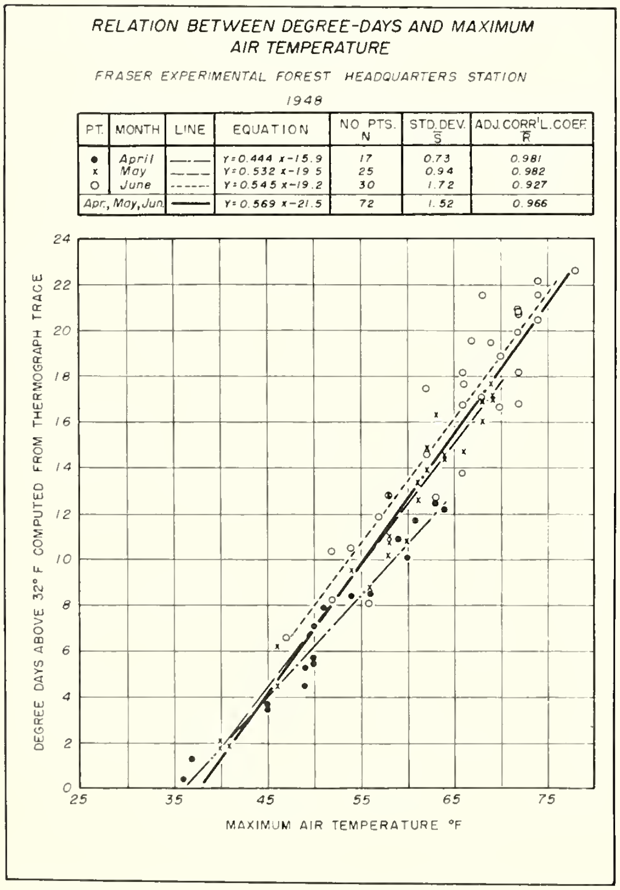


Figure 14. Relation between degree-days and maximum air temperature, Headquarters Station, 1948.

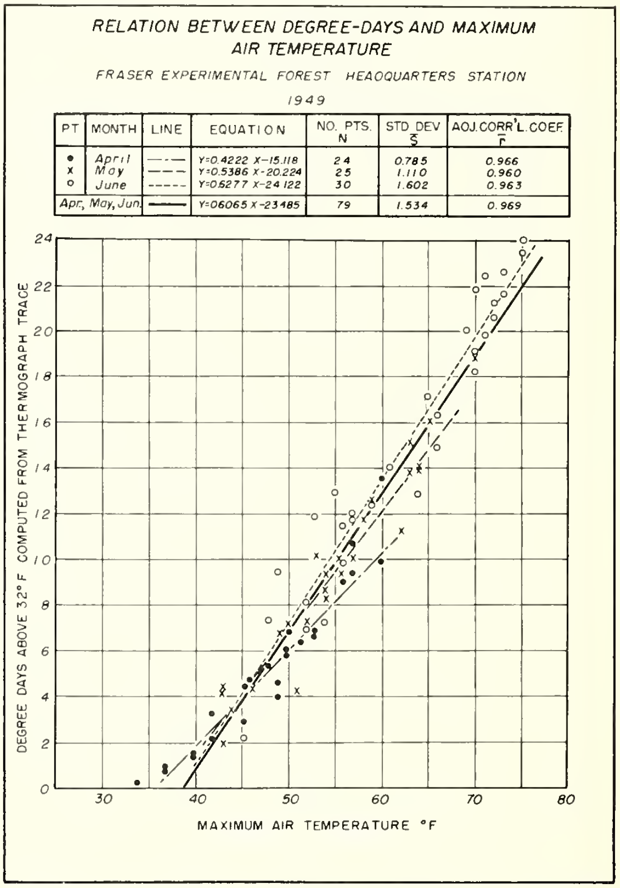


Figure 15. Relation between degree-days and maximum air temperature, Headquarters Station, 1949.

mum air temperature does not appear to be significantly better than the relationship to maximum temperature alone.

The relation of the maximum temperature and the average of maximum and minimum temperatures with the degree-days derived from a thermograph trace was explored at two other stations. The thermograph at Shadow Mountain Camp of the Bureau of Reclamation's Colorado-Big Thompson Project near Grand Lake, Colo., was

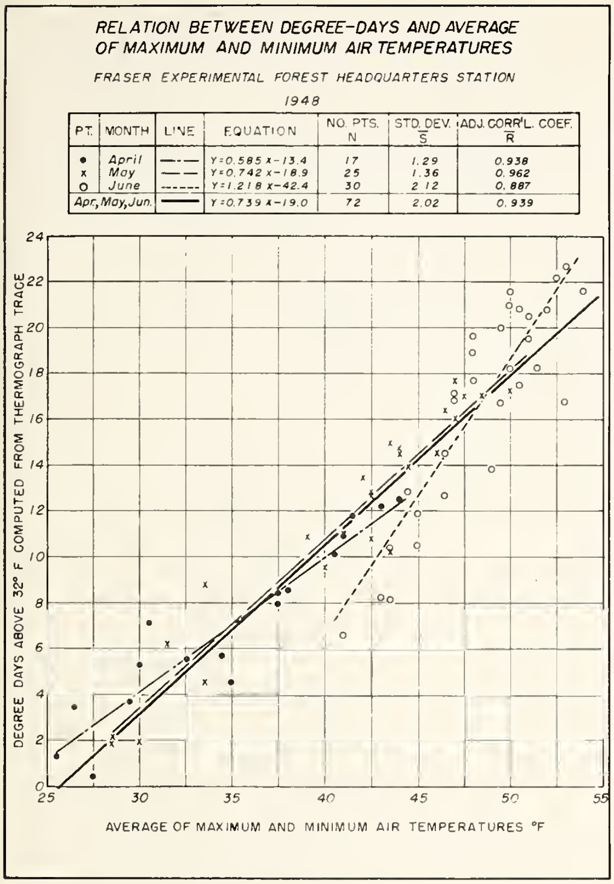


Figure 16. Relation between degree-days and average of maximum and minimum air temperatures, Headquarters Station, 1948.

located at an elevation of 8,389 feet. The thermograph at Redcliff, Colo., 55 miles airline distance SSW from the Shadow Mountain Camp, is at an elevation of 8,608 feet above sea level. The relation between the maximum air temperature and the degree-days above 32 computed from thermograph trace for these stations is illustrated by figures 20 and 21. Both of these charts indicate a very strong relation between maximum air temperature and the degree-days above 32. A summary of the comparisons of maximum temperature and daily average temperatures with degree-days for Shadow Mountain Camp, Redcliff, Colo., and the Fraser Experimental Forest Headquarters Station, for certain months of 1947 and 1948 is given in table 2.

The effect of short distance displacement and difference in exposure of the thermograph locations is illustrated by the comparison between degree-days at Fool Creek and West St. Louis Stations shown on figure 22. Both stations are at an elevation of 9,500 feet, but the Fool Creek Station is in a heavily wooded area whereas the West St. Louis Station is in an open meadow.

Reasonably high correlation coefficients were obtained between degree-days, as computed from hourly values on the thermograph trace, and the maximum temperature, or the average of the maximum and the effective minimum temperatures. Possibly the latter relation would give a better representation of the heat factor to use in correlation studies with runoff. The use of the maximum temperature requires the least effort, since maximum temperatures are readily available in the Weather Bureau's climatological data summaries, and the use of this factor requires no additional computations. Other methods of interpreting degree-days, such as the introduction of the effective minimum temperature and dwell time of temperatures above 32° may require considerable work. Among the refinements used in this type of correlation is the one by Snyder, re-

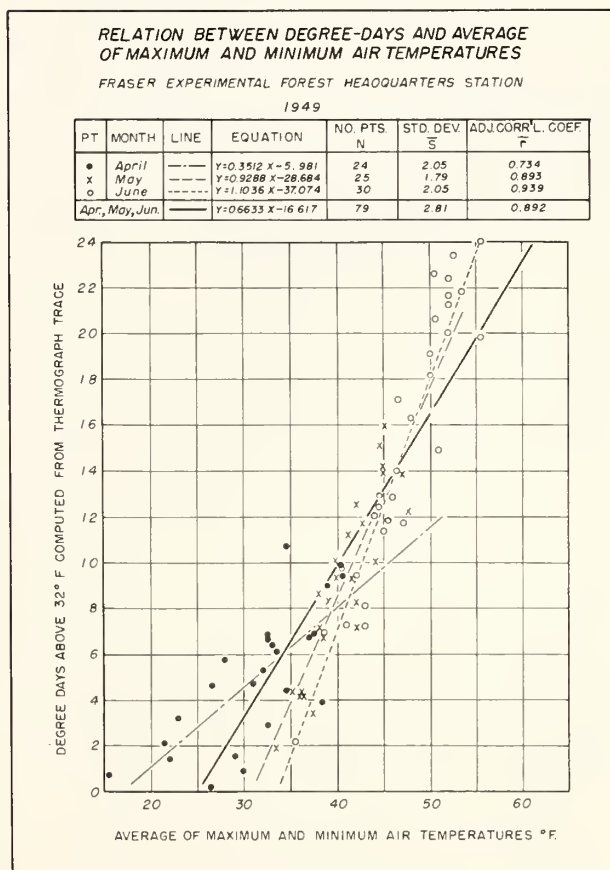


Figure 17. Relation between degree-days and average of maximum and minimum air temperatures, Headquarters Station, 1949.

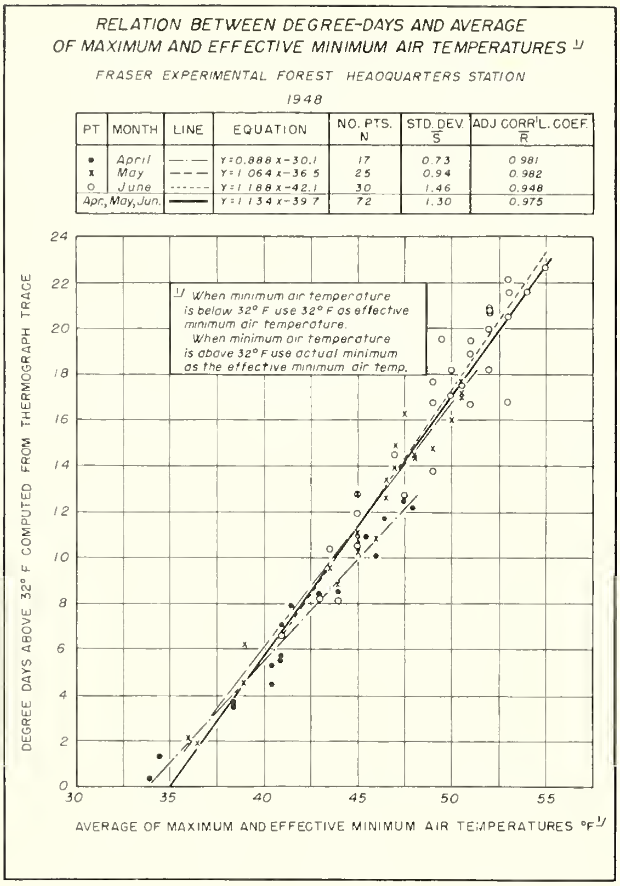


Figure 18. Relation between degree-days and average of maximum and effective minimum air temperatures, Headquarters Station, 1948.

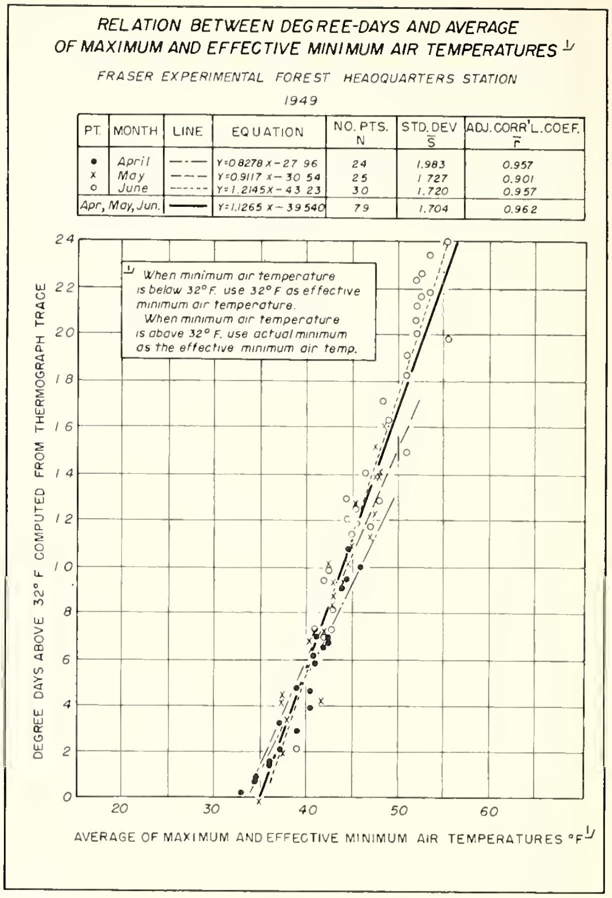


Figure 19. Relation between degree-days and average of maximum and effective minimum air temperatures, Headquarters Station, 1949.

Table 2—Summary of degree-day equations for Shadow Mountain, Redcliff, and Headquarters Station

Degree-days (Y) as computed from hourly values of hygrothermograph records in relation to daily maximum temperature (X) and to the average of daily maximum plus minimum temperature (X).

Comparison with maximum temperature					Comparison with average of maximum plus minimum temperature	
Station	Year	Month	Relationship	Equation	Relationship	Equation
Shadow Mountain	1948	April	Curvilinear	None	Linear	None.
Do	1948	May	Linear	Y=0.701X−27.6	do	Y=0.984X−29.9
Do	1948	June	do	Y=0.562X−17.9	do	Y=1.27X −45.7
Redcliff, Colorado	1948	April	do	Y=0.476X−17.1	do	Y=0.755X−19.9
Do	1948	May	do	Y=0.622X−24.0	do	Y=1.09X −35.0
Do	1948	June	do	Y=0.646X−24.6	do	Y=1.44X −53.8
Fraser Experimental Forest, Hq. Sta.	1948	April	do	Y=0.444X−10.9	do	Y=0.585X−13.4
Do	1948	May	do	Y=0.532X−19.5	do	Y=0.742X−18.9
Do	1948	June	do	Y=0.545X−19.2	do	Y=1.218X−42.4
Do	1947	May	do	Y=0.525X−19.4	do	Y=1.01X −31.7
Do	1947	June	do	Y=0.634X−24.7	do	Y=1.13X −35.8
Do	1947	July	Curvilinear	None	do	Y=1.78X −72.7

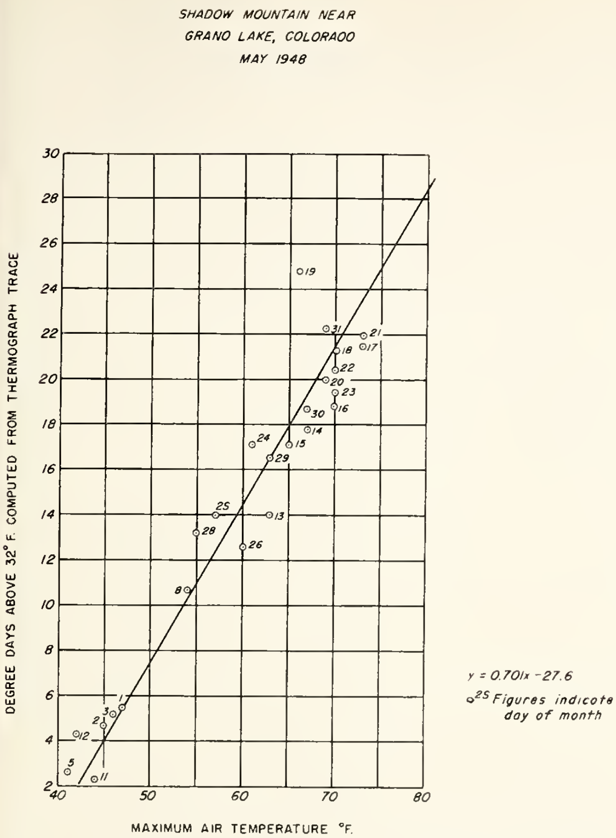


Figure 20. Relation between degree-days and maximum air temperature, Shadow Mountain near Grand Lake, Colo., May 1948.

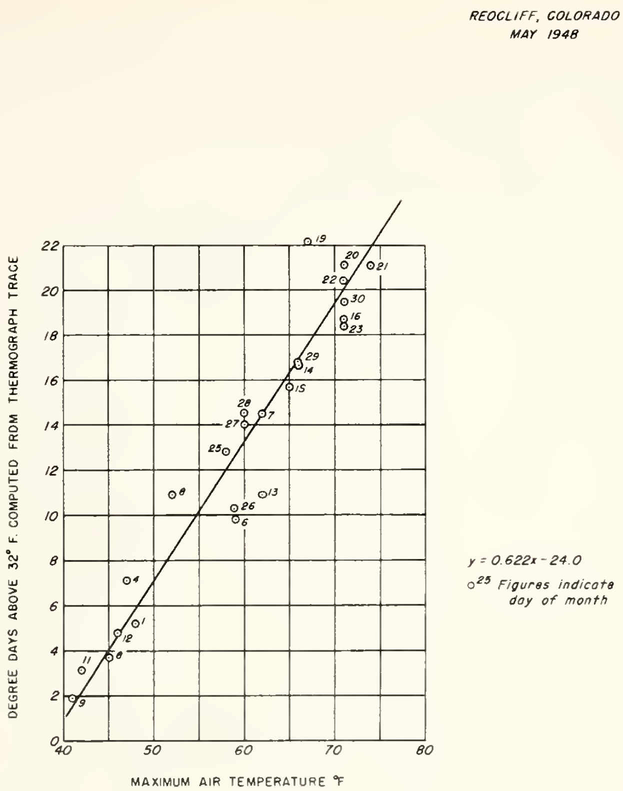


Figure 21. Relation between degree-days and maximum air temperature, Redcliff, Colo., May 1948.

ferred to by Linsley, Kohler, and Paulhus [65].[4] Slater [81] also developed a method which recognizes the spread between the daily maximum and minimum temperatures, and which was tested on the Fraser Experimental Forest data as explained below.

Slater drew a family of curves by eye for 10° F intervals of daily range in temperature on a chart correlating maximum air temperature and degree-days above 32, computed from the thermograph trace. His technique was applied to data for May and June 1949 from the Fraser Experimental Forest Headquarters Station, as is shown in figure 23. The degree-days above 32, estimated by using figure 23 for May and June 1949, are shown in figure 24; the latter indicates how well the family of curves fits the data. A test of this

[4] Reference 65, page 28.

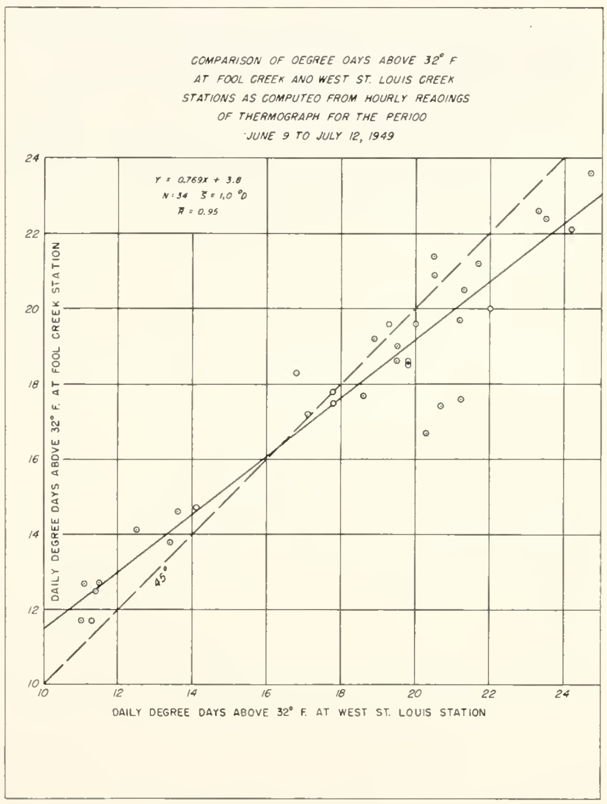


Figure 22. Comparison of degree-days at Fool Creek and West St. Louis Creek Stations

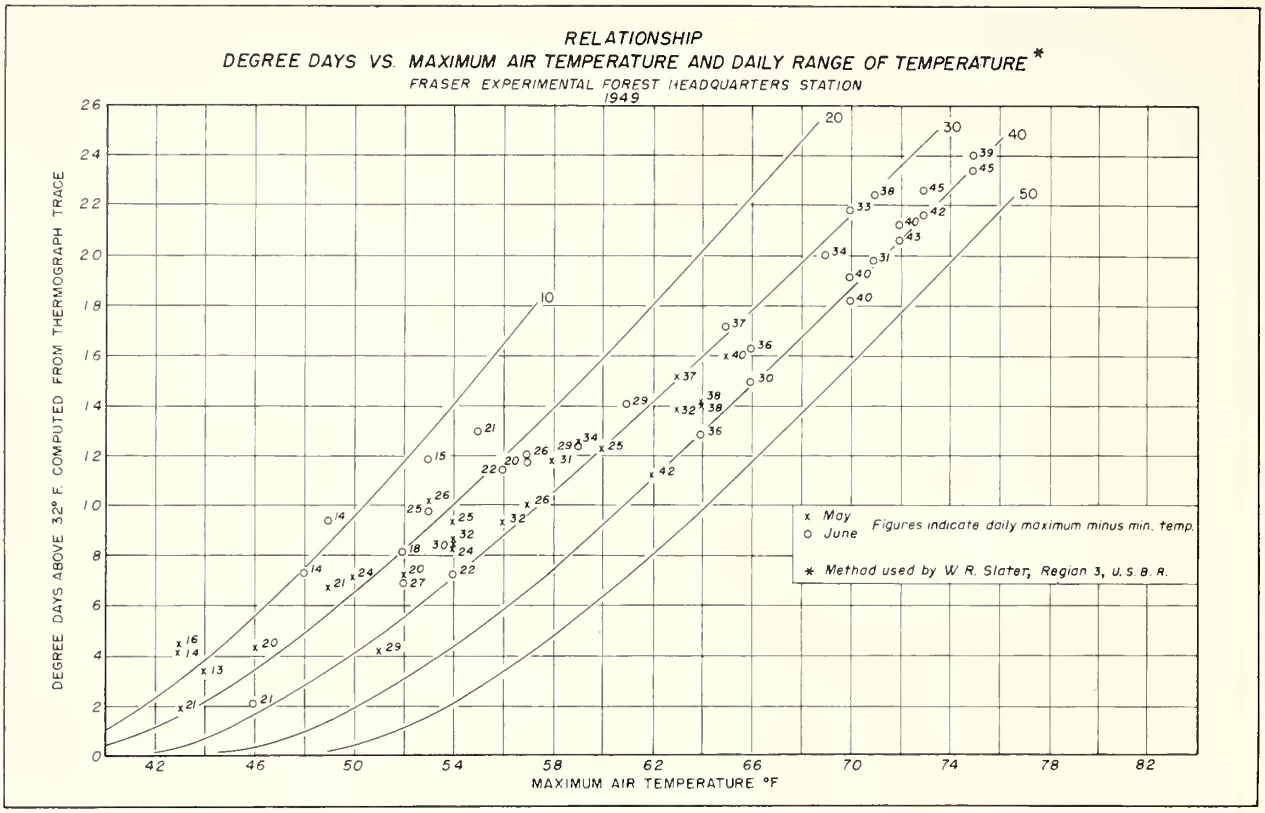


Figure 23. Slater method for relating maximum air temperatures and range in temperature to degree-days as applied to Headquarters Station, 1949.

relation, not employing data used in its derivation, is shown in figure 25 for June 1948.

Many hydrologists make a reconnaissance-type estimate of snowmelt runoff by use of the factor of snowmelt runoff per degree-day. Table 3 shows the values of this factor as observed at the Fraser Experimental Forest for degree-days estimated in different ways. The table illustrates the variation in this factor during the active snowmelt period. Table 4 shows the average value of this factor for the active snowmelt periods in 1948, 1949, and 1950.

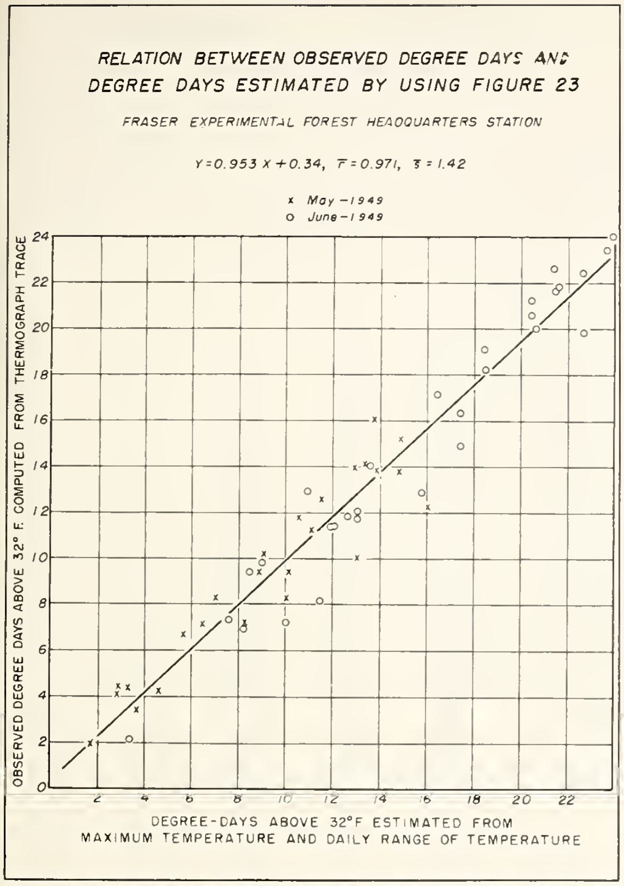


Figure 24. Relation between observed degree-days and degree-days estimated from maximum air temperature and daily range of temperature, May and June 1949.

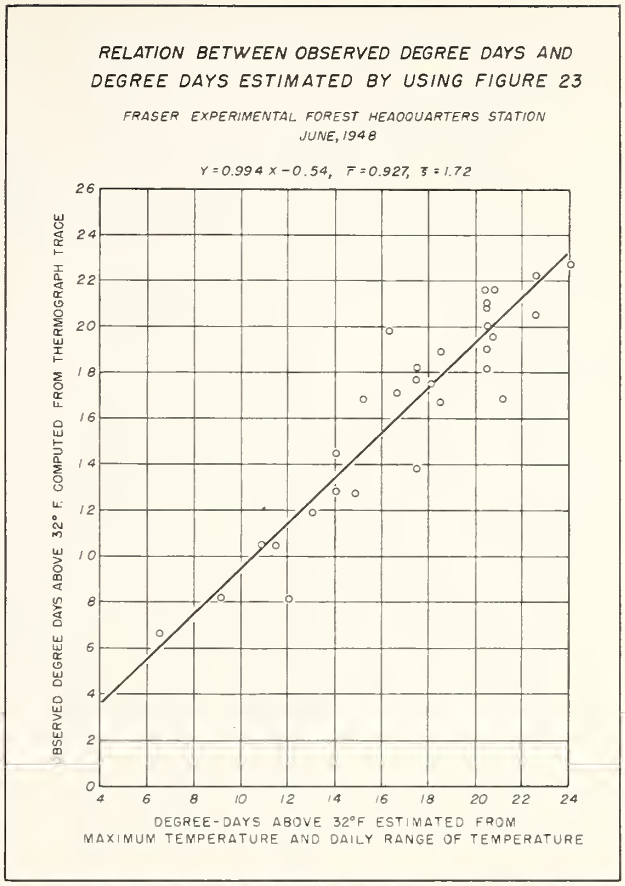


Figure 25. Relation between observed degree-days and degree-days estimated from maximum air temperature and daily range of temperature, June 1948.

Table 3—Values of the ratio, snowmelt runoff per degree-day, for May and June 1950

Date	Runoff, St. Louis Creek [1] (inches)	Thermometer at headquarters station: Maximum temperature (°F)	Thermometer at headquarters station: Minimum temperature (°F)	Thermometer at headquarters station: Average of maximum and minimum temperature (°F)	Degree-days and runoff ratios: Hygrothermograph: Degree-days	Hygrothermograph: Runoff per degree-day B/F	Maximum temperature only: Degree-days	Maximum temperature only: Runoff per degree-day B/H	Average of maximum and minimum temperature: Degree-days	Average of maximum and minimum temperature: Runoff per degree-day B/J
A	B	C	D	E	F	G	H	I	J	K
1950										
May 13	.106	53	21	37.0	7.9	.0134	21	.0050	5.0	.0212
14	.174	58	21	39.5	11.5	.0151	26	.0067	7.5	.0232
15	.025	56	28	42.0	8.0	.0031	24	.0010	10.0	.0025
16	.174	57	27	42.0	10.3	.0169	25	.0070	10.0	.0174
17	.156	66	24	45.0	13.2	.0118	34	.0046	13.0	.0120
18	(−.035)	51	27	39.0	6.6	(−.0053)	19	(−.0018)	7.0	(−.0050)
19	.054	53	19	36.0	8.2	.0066	21	.0026	4.0	.0135
20	.103	54	27	40.5	7.7	.0134	22	.0047	8.5	.0121
21	.216	63	21	42.0	12.5	.0173	31	.0070	10.0	.0216
22	.193	67	23	45.0	16.2	.0119	35	.0055	13.0	.0148
23	.188	67	26	46.5	15.4	.0122	35	.0054	14.5	.0130
24	.012	60	30	45.0	10.0	.0012	28	.0004	13.0	.0009
25	(−.020)	34	21	27.5	0.4	(−.0500)	2	(−.0100)	(−4.5)	.0044
26	(−.086)	44	21	32.5	3.2	(−.0269)	12	(−.0072)	0.5	(−.1720)
27	.010	49	27	38.0	7.0	.0014	17	.0006	6.0	.0017
28	.053	58	28	43.0	8.2	.0065	26	.0020	11.0	.0048
29	.050	53	27	40.0	8.0	.0062	21	.0024	8.0	.0062
30	.280	65	26	45.5	15.5	.0181	33	.0085	14.5	.0207
31	.306	61	23	42.0	13.2	.0232	29	.0106	10.0	.0306
June 1	.364	69	21	45.0	16.5	.0221	37	.0098	13.0	.0280
2	.298	69	24	46.5	13.9	.0214	37	.0080	14.5	.0206
3	(−.209)	36	25	30.5	1.1	(−.1900)	4	(−.0522)	(−1.5)	.1393
4	.101	56	19	37.5	7.0	.0144	24	.0042	5.5	.0184
5	.328	70	25	47.5	15.5	.0212	38	.0086	15.5	.0212
6	.558	72	26	49.0	22.1	.0252	40	.0140	17.0	.0328
7	.235	68	27	47.5	16.0	.0147	36	.0065	15.5	.0152
8	(−.065)	51	20	35.5	8.2	(−.0079)	19	(−.0034)	3.5	(−.0186)
9	.349	63	18	40.5	12.9	.0270	31	.0112	8.5	.0410
10	.532	75	26	50.5	20.5	.0260	43	.0124	18.5	.0288
11	.496	79	25	52.0	22.4	.0221	47	.0106	20.0	.0248
12	.310	78	25	51.5	21.4	.0145	46	.0067	19.5	.0159
13	.399	77	27	52.0	21.8	.0183	45	.0089	20.0	.0200
14	.348	78	26	52.0	22.2	.0157	46	.0076	20.0	.0174
15*	.729	80	26	53.0	24.4	.0299	48	.0152	21.0	.0347
16	.620	76	35	55.5	24.2	.0256	44	.0141	23.5	.0264
17	.124	79	33	56.0	23.3	.0053	47	.0026	24.0	.0052
18	(−.224)	73	23	48.0	19.8	(−.0113)	41	(−.0054)	16.0	(−.0140)
19	.088	72	29	50.5	19.7	.0045	40	.0022	18.5	.0048
20	.119	69	29	49.0	16.4	.0072	37	.0032	17.0	.0070
21	.094	73	27	50.0	17.5	.0054	41	.0023	18.0	.0052
22	.039	66	26	46.0	17.6	.0022	34	.0011	14.0	.0028
23	.116	77	29	53.0	23.0	.0050	45	.0026	21.0	.0055
24	.076	79	30	54.5	23.2	.0033	47	.0016	22.5	.0034
25	(−.018)	69	31	50.0	21.0	(−.0008)	37	(−.0005)	18.0	(−.0010)
26	.047	77	26	51.5	22.5	.0021	45	.0010	19.5	.0024
27	.083	74	30	52.0	21.5	.0039	42	.0020	20.0	.0042
28	.144	74	27	50.5	22.3	.0064	42	.0034	18.5	.0078
May 13–16	.479				37.7	.0127	96	.0050	32.5	.0147
May 17–31	1.480				145.3	.0102	365	.0040	127.5	.0116
June 1–15	4.773				245.9	.0194	541	.0088	210.5	.0227
June 16–28	1.308				272.0	.0048	542	.0024	250.5	.0052
Total, May 13 to June 28	8.040				700.9	.0115	1,544	.0052	621.0	.0129

*Day having maximum runoff volume.

[1] Volume including recession volume.

Table 4—Summary of factors, runoff per degree-day for 1948, 1949, and 1950

Period	Total runoff volume (inches)[1]	Runoff per degree-day (inches per degree-day)		
		Degree-days from thermograph	Degree-days of daily maximum temperature	Degree-days from average of daily maximum and minimum temperature
1948				
May 14–17	0. 753	0. 0178	. 0081	. 0221
May 18–June 1*	3. 352	. 0161	. 0075	. 0175
June 2–5	0. 969	. 0136	. 0065	. 0148
May 14–June 5	5. 074	. 0158	. 0074	. 0175
1949				
May 19–June 1	1. 298	. 0095	. 0039	. 0100
June 2–16*	4. 329	. 0245	. 0115	. 0225
June 17–20	0. 782	. 0112	. 0057	. 0109
May 19–June 20	6. 409	. 0167	. 0076	. 0162
1950				
May 13–16	0. 479	. 0127	. 0050	. 0147
May 17–31	1. 480	. 0102	. 0040	. 0116
June 1–15*	4. 773	. 0194	. 0088	. 0227
June 16–28	1. 308	. 0048	. 0024	. 0052
May 13–June 28	8. 040	. 0115	. 0052	. 0129

*Day having maximum runoff volume.
[1] Runoff including recession volume.

SECTION 5—SEASONAL STORAGE PRECIPITATION GAGES

In seasonal water-yield forecasting, there is a definite practical application of precipitation storage gage records, not as substitutes for water equivalent data obtained by snow surveys, but as another and independent evaluation of one of the most important hydrologic factors affecting streamflow and water yield.

A snow survey yields data on the residual water equivalent remaining in the drainage basin on the date of the survey. The snow survey, by itself, does not indicate what the net balance is between the snowfall, the snowmelt, the evaporation, and the rainfall which may have occurred during the interval between surveys. A May 1 snow survey would merely give the water equivalent remaining on the date of the survey. Between the April 1 and the May 1 surveys, a certain amount of melt may have occurred, and a certain amount of rain and snow may have fallen. The snowmelt and the rainfall would certainly have an influence on the priming of the soil to replenish moisture deficits caused by evapotranspirational losses of the preceding fall.

Thus, a knowledge of the hydrologic events which may have occurred between the dates of the snow surveys would give a potentially very useful additional variable to be used in the calculation of seasonal water-yield forecasts. Accordingly, the cooperative snow investigations at the Fraser Experimental Forest included the installation of the Sacramento-type seasonal storage precipitation gages as described in appendix A. The activation of this system is described by Johnson [56]. Five gages of 100-inch capacity and one gage of 200-inch capacity were installed at the locations shown in figure 2. They were equipped with a modified form of the Alter shield.

The results of the observations at the six Sacramento rain-gage installations, together with snow surveys performed at the gaging stations, are given in table 5, and illustrated graphically in figure 33. Photographs of the gages in use are shown in figures 26–32.

It is evident, on inspection of the April 1 data and of a study of the photographs taken at the time the various gages were measured in 1947 and 1948, that the gages did not indicate very well the precipitation accumulated during the winter season. The photographs show the pro-

Figure 26. April 3, 1947. The St. Louis Pass gage at elevation 10,330 feet. This is a 200-inch-capacity Sacramento-type seasonal storage precipitation gage. The water equivalent gage increment after October 25, 1946, was 21.00 inches, as compared with the snow-water equivalent on the ground determined by 10 samples taken in the vicinity of the gage, of 23.11 inches. Note the blanket of snow on the platform and the cylinder of snow extending from the shield. It appears that the cylinder within and below the shield is formed by snow packing down from above as restrained by the shield and not by snow building up from the platform.

Table 5—Summary of seasonal storage precipitation gage records and of snow surveys at gage sites, 1947 through 1951

Year	Date	Station elevation (feet) capacity (inch) condition	East St. Louis Creek 9,520, 100 shielded		Iron Creek 9,680, 100 shielded		Range Creek 9,360, 100 shielded		St. Louis Pass 10,330, 200 unshielded		West St. Louis Creek 9,840, 100 shielded		West St. Louis Creek 9,840, 100 unshielded	
			Date or period	Water equivalent (inch)	Date or period	Water equivalent (inch)	Date or period	Water equivalent (inch)	Date or period	Water equivalent (inch)	Date or period	Water equivalent (inch)	Date or period	Water equivalent (inch)
1947	April 1	Gage increment	11-17-46 to 4-1-47	[6] 9.25	11-16-46 to 4-1-47	[2] 11.25	11-16-46 to 4-1-47	[6] 9.25	*10-25-46 to 4-3-47	[6] 21.00	11-17-46 to 4-2-47	[6] 10.40	------	------
		Snow survey	4-1-47	13.80	4-1-47	11.75	4-1-47	14.15	4-3-47	23.11	4-2-47	28.77	------	------
	May 1	Gage increment	4-1-47 to 5-2-47	3.50	4-1-47 to 4-29-47	4.00	4-1-47 to 4-29-47	3.50	*4-3-47 to 4-30-47	5.80	4-2-47 to 4-29-47	4.15	------	------
		Snow survey	5-2-47	14.92	4-29-47	12.92	4-29-47	15.42	4-30-47	23.32	4-29-47	23.92	------	------
1948	April 1	Gage increment	9-27-47 to 4-2-48	[5] 12.50	9-26-47 to 3-31-48	[1] 13.50	9-26-47 to 3-31-48	[4] 12.00	*9-26-47 to 4-1-48	[6] 16.50	9-25-47 to 4-2-48	[6] 18.00	------	------
		Snow survey	4-2-48	14.35	3-31-48	11.25	3-31-48	13.40	4-1-48	18.95	4-2-48	20.25	------	------
	May 1	Gage increment	4-2-48 to 4-28-48	3.00	3-31-48 to 5-4-48	4.00	3-31-48 to 5-4-48	4.50	*4-1-48 to 5-4-48	9.00	4-2-48 to 4-29-48	5.50	------	------
		Snow survey	4-28-48	10.65	5-4-48	6.10	5-4-48	10.15	5-4-48	18.55	4-29-48	16.96	------	------
1949	April 1	Gage increment	9-22-48 to 4-8-49	[6] 11.7	10-2-48 to 4-12-49	[1] 13.3	10-1-48 to 4-12-49	[3] 10.8	10-1-48 to 4-12-49	[6] 17.3	9-28-48 to 4-7-49	[3] 18.1	9-28-48 to 4-7-49	[6] 15.8
		Snow survey	4-8-49	14.0	4-12-49	10.7	4-12-49	11.6	4-12-49	20.0	4-7-49	19.1	4-7-49	19.1
	May 1	Gage increment	4-8-49 to 5-2-49	1.8	4-12-49 to 5-3-49	2.0	4-12-49 to 5-3-49	1.8	4-12-49 to 5-3-49	2.8	4-7-49 to 4-29-49	2.3	4-7-49 to 4-29-49	1.4
		Snow survey	5-2-49	11.3	5-3-49	0.0	5-3-49	8.1	5-3-49	18.5	4-29-49	14.7	4-29-49	14.7
1950	April 1	Gage increment	8-30-49 to 3-31-50	[1] 16.2	9-2-49 to 3-30-50	[1] 12.8	9-1-49 to 3-30-50	[6] 8.4	9-12-49 to 3-30-50	[6] 14.6	9-13-49 to 3-29-50	[6] 17.3	9-13-49 to 3-29-50	[6] 14.3
		Snow survey	3-31-50	15.9	3-30-50	12.55	3-30-50	12.35	3-30-50	19.92	3-29-50	21.6	3-29-50	21.6
	May 1	Gage increment	3-31-50 to 5-1-50	3.3	3-30-50 to 4-28-50	3.9	3-30-50 to 4-28-50	2.5	3-30-50 to 4-28-50	5.6	3-29-50 to 5-2-50	5.15	3-29-50 to 5-2-50	4.25
		Snow survey	5-1-50	15.6	4-28-50	9.4	4-28-50	13.3	4-28-50	22.6	5-2-50	20.8	5-2-50	20.8
1951	April 1	Gage increment	10-2-50 to 4-7-51	[5] 16.9	------	------	------	------	------	------	10-4-50 to 3-30-51	[6] 18.6	10-4-50 to 3-30-51	[6] 18.1
		Snow survey	4-7-51	18.5	------	------	------	------	------	------	3-30-51	21.1	3-30-51	21.1

*Gage shielded in 1947 and 1948.
Following superscript numbers classify the April 1 readings:
[1] Gage catch equal to or greater than snow course reading.
[2] Gage catch 0.1 to 0.5 inch less than snow course reading.
[3] Gage catch 0.6 to 1.0 inch less than snow course reading.
[4] Gage catch 1.1 to 1.5 inches less than snow course reading.
[5] Gage catch 1.6 to 2.0 inches less than snow course reading.
[6] Gage catch more than 2.0 inches less than snow course reading.

Figure 27. June 14, 1947. The East St. Louis Creek seasonal storage precipitation gage, 100-inch-capacity Sacramento-type, with Alter shield, as it appeared after the snowfall of June 14, 1947. The snow had a depth of 14 inches and a water equivalent of approximately 2 inches. This was sufficient to lodge in the space between the shield and the gage.

clivity of the gages to capping by snow under the conditions of use in this study. The comparisons in table 5 of the April 1 data for gage increment and from snow surveys made immediately around the gage reveal wide discrepancies. For all but one site the gage catch is consistently less than the water equivalent of the snow pack even though the pack is subject to reduction by sublimation whereas the gage catch is not. Only the April 1 data may be used for such a comparison because melting of the pack usually begins before May 1. In figure 33, the comparisons between gage catches and water equivalents of the snowpack are presented in bar-graph form.

The gages were installed in the autumn of 1946. At that time, steel was not procurable for constructing supporting towers. Therefore, the gages were installed upon wooden towers. Although the wooden towers accumulated a certain amount of snow, as is shown in figure 26, the depth of snow on the platforms supporting the gages did not interfere with the action of either the shield or of the gage.

The behavior of the East St. Louis Creek gage during a sudden snowstorm on June 14, 1947, shows the effect of a snowfall of 14-inch depth having a water equivalent or approximately 2 inches. As shown in figure 27, the gage was not put out of commission by snow accumulating on the diverging walls of the body or on the wooden supports, but by snow lodging in the hopper created between the converging slats of the Alter shield and the walls of the rain gage. Had this snowstorm occurred in the fall, subsequent snowfalls would undoubtedly have capped over the mouth of the shield. This may be the chief reason for the nature of the observations recorded in table 5.

Figure 28. April 1, 1948. The East St Louis Creek gage, Fraser Experimental Forest, near Fraser, Colo. This is a 100-inch-capacity Sacramento-type seasonal storage precipitation gage installed at an elevation of 9,520 feet. The water equivalent gage increment after September 25, 1947, the date of servicing, amounted to 12.50 inches, as compared with 14.35 inches determined by a 10-sample snow survey in the vicinity of the gage.

One possible reason why the shields and the Sacramento-type gages have not performed adequately under the conditions of the Rocky Mountains in Colorado is that many of the snowstorms fall at times of very low wind velocities. Furthermore, the gages are sheltered in lodgepole pine and spruce-fir type forests. The protective effects of the tree growth are evidently so potent that there is practically no wind blowing within the crown canopy zone at the time of the snowfall. Therefore, the shield on the storage gage is not called upon to perform any useful service, and it merely acts as a ledge upon which snow can accumulate.

Wilson [104] concluded that much of the variation in the catchment of precipitation of rugged areas from 4 to 20 square miles in size can be ascribed to variations in the local exposure and in the natural sheltering of the gages. Wind speed appears to be a good measure of the adequacy of gage sheltering. Wind speeds at the gage orifice should average less than 2 miles per hour. Openings in the forest having a diameter about equal to the height of the trees appear, according to Wilson, to be best for precipitation gage locations. This conclusion of Wilson's is at variance with the usual rule applied to cooperative weather instrument installations that the gage should be no nearer than two to four times the height of the nearest object. Undoubtedly, the wind pattern in the vicinity of one large object, such as a single building, would be completely different from that in an opening surrounded by tree growth.

It appears that much of the emphasis upon shielding of seasonal storage precipitation gages and upon aerodynamic streamlining of the gages themselves has not taken cognizance of the fact that snow falling during the heavy snowfalls will stick to practically anything. Examination of the weather charts kept by Borland [16] in connection with his avalanche research work on

Figure 29. April 1, 1948. Snow survey being performed at the West St. Louis Creek seasonal storage precipitation gage, elevation 9,840 feet, in the Fraser Experimental Forest near Fraser, Colo. The water equivalent increment in the gage after September 25, 1947, amounted to 18.00 inches, as compared with 20.25 inches water equivalent as determined by a 10-sample snow survey being performed.

Figure 30. April 1, 1947. The Iron Creek gage at an elevation of 9,680 feet above sea level in the Fraser Experimental Forest, Colorado, is a Sacramento-type seasonal storage precipitation gage of 100-inch capacity. The water equivalent increment after November 16, 1946, was 11.25 inches, as compared with the water equivalent of a snow course based upon 10 samples surveyed in the vicinity of the gage of 11.75 inches.

Figure 31. April 2, 1947. The West St. Louis Creek gage, an 100-inch-capacity Sacramento-type seasonal storage precipitation gage at 9,840 feet above sea level. The water equivalent gage increment after November 17, 1946, was 4.80 inches in the gage and 10.40 inches, including the snow samples in the mushroomlike top, as compared with a water equivalent of 28.77 inches as measured in a 10-sample snow course located in the immediate vicinity of the gage.

Berthoud Pass indicates that the winter snowfalls are usually small and have densities of about .05. The larger snowstorms usually occur in the fall and spring with individual storms depositing up to 2 inches water equivalent of new snow which has densities of 0.10 or more. While records of individual storms were not kept at the Fraser Experimental Forest, it has been observed that the snow falling during the winter is generally feathery and of very low density, averaging about 0.05. The capping of the gages shown in the pictures apparently is the result of one or two heavy falls of relatively wet snow in late March and spring or possibly the preceding fall, followed by cold spells which freeze the cap in place.

This is illustrated by the weather record for the June 1947 snowstorm which caused the capping shown in figure 27. The precipitation gage at Fraser shows that the following amounts of pre-

Figure 32. May 1, 1947. West St. Louis Creek gage one month later than figure 31. The gage and shield had been cleared of accumulated snow on April 1, but new snow during April produced this result. Total depth of snow here is 70 inches. Gage was subsequently moved into a more open spot and mounted on a higher tower.

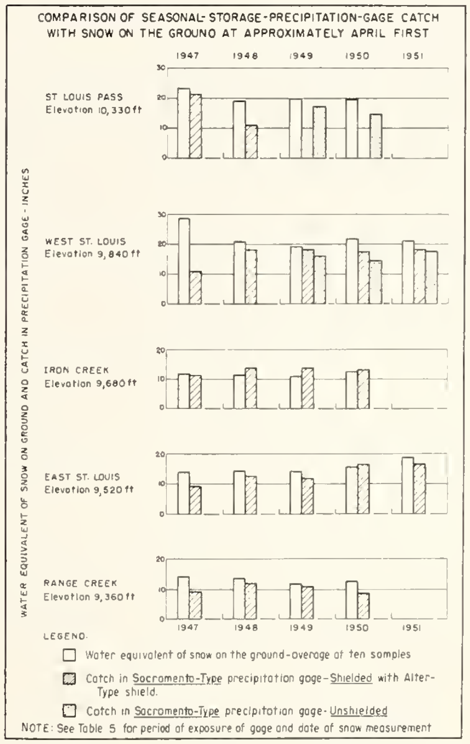


Figure 33. Comparison of seasonal storage precipitation gage catch with snow on the ground at approximately April 1.

cipitation were recorded: June 9, 0.30 inch; June 11, 0.90 inch; June 12, 0.80 inch; and June 13, 0.05 inch, for a total of 2.05 inches. This resulted in new snow in the Fraser Experimental Forest having a depth of 14 inches and water equivalent of about 2 inches. The relative humidity at the Headquarters Station was between 80 and 100 percent from noon on June 9 to 7:00 a. m. on June 10, from 4:00 a. m. on June 11 to 9:00 a. m. on June 12, and from noon on June 12 to 6:00 a. m. on June 13. Air temperatures during this period varied between 23° F and 41° F until the early morning of June 13 when the temperature dropped to 13° F. During the most intense period of the storm, June 11 and 12, the temperatures ranged from 27° F to 41° F.

A similar phenomenon was noted in Idaho by Warnick [98].

Experiences with snowcapping of the gages in the Fraser Experimental Forest led to the development of a new precipitation gage in conjunction with the development and activation of a network of radio-reporting precipitation gages in the Sacramento River drainage basin below Shasta Dam as part of the Bureau of Reclamation's hydrologic data-gathering facilities for the Central Valley project, California. This radio-reporting network is described in [87].

Allen, Glover, Garstka, and Posz [2] described the design and functioning of a heated precipitation gage intake tube in which heat is transported to a specially constructed intake tube through a vapor-phase system using an evaporable liquid having a boiling point of about 40° F at a pressure of one atmosphere. The gage is heated by combustion of liquefied petroleum gas in a vented space heater which operates intermittently under thermostatic control. The system provides sufficient heat to prevent snow and ice from adhering to a precipitation gage intake tube, thus inhibiting the usual capping over and incapacitation of gages operating under winter conditions at elevations where the precipitation may fall as rain, snow, sleet, and slush, and in various successive combinations of these forms of precipitation during a single storm. Figure 34 is a diagrammatic arrangement of apparatus for the heated precipitation gage intake tube as used in the Central Valley project.

The United States Patent Office has granted a public patent [1] on the heated precipitation gage intake tube. The precipitation gage heated intake tube has been incorporated in a seasonal storage precipitation gage placed in the drainage basin of Eklutna Lake at the Bureau of Reclamation's Eklutna project in Alaska. The essential features of both the Central Valley project radio-reporting system heated intakes and the Eklutna intake are the same, with the exception that the controls for the Eklutna gage are primarily mechanical, and the heated intake has been incorporated in a modification of the Weather Bureau's so-called

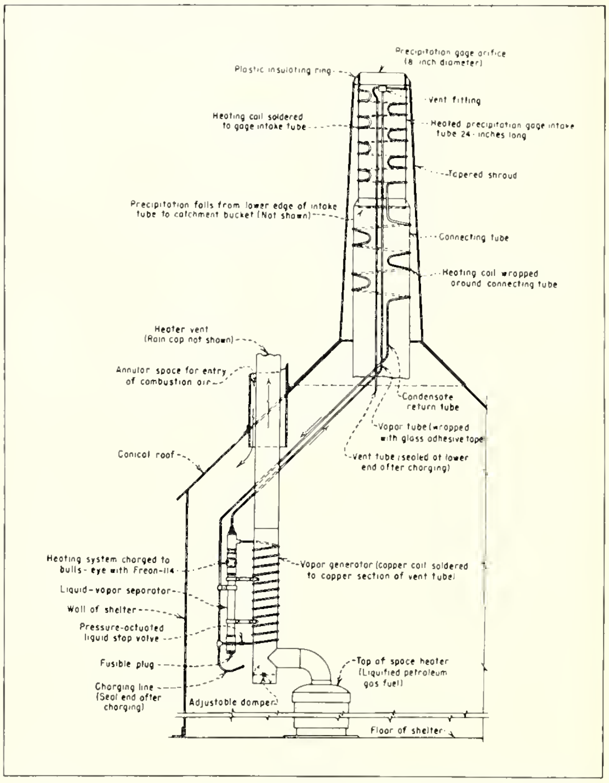


Figure 34. Diagram of apparatus for heated precipitation gage intake tube as used in the Central Valley project, California.

"Standpipe" type of gage. The Eklutna gage is described in Reference 31.

The objective of the heated precipitation gage intake tube is to prevent the adherence of wet snow or sleet. The usual storm history in the mountainous regions of the West is for a moisture-bearing front to be followed by a sudden and, at times, deep depression of air temperatures. Such a freezing following a sticky snowstorm usually anchors the adhering snow which then stays there and is augmented by contributions from subsequent snowstorms, ultimately resulting in the capping similar to that illustrated in figures 26

through 32. However, there are numerous storms consisting either of rainfall or of frozen snow at temperatures much below 32°, for which the heated intake is not necessary but which do require adequate shielding of the intake orifice of a precipitation gage.

An appreciation of the importance of shielding precipitation gages is not new, as is evidenced by Nipher's publication of 1878 [76].

The shields used with the Sacramento storage gages in the Fraser Experimental Forest were modifications of the Alter shield. Original developmental work dating back to 1909 is described by Alter [3].

A comprehensive discussion of the influence of wind on precipitation measurements is given by Warnick [97].

One of the problems inherent in the operation and maintenance of seasonal storage precipitation gages is that of incorporating into the catchment the storm-by-storm increments of precipitation and protecting them against loss by evaporation from the gage. Antifreeze solutions in the gage and protective layers of oil have been used in the endeavors to attain this objective. A detailed discussion of the use of antifreezes and anti-evaporants in precipitation gages is given in appendix A.

SECTION 6—SNOW DISAPPEARANCE

Practically all of the water yield from the St. Louis Creek drainage basin is the result of water released by the spring melting of snow. A correlation between disappearance of the snow cover and increase in streamflow is thus to be expected. Furthermore, in the Rocky Mountains, the timing of snowmelt is very largely a function of the intensity of incident solar radiation and altitude. The former is, in turn, a function of aspect and slope. Thus, for a given area, there tends to be a normal pattern of snow disappearance. The ground becomes bare first on south slopes at lower elevations. West and east slopes at these same elevations, and south slopes at higher altitudes, become bare next with north slopes at high elevations holding their snow longest. The presence or absence of forest makes less definite, but does not destroy, the pattern associated with topography. This consistency in the progression of snowmelt renders feasible mapping or otherwise recording the disappearance of the snow pack.

Such a record for the St. Louis Creek watershed was made in the spring of 1950 along with snow surveys to indicate the decline of the volume of water equivalent in the snow pack. Supplemental studies were also made to gain insight into the effects of forests and topography on snowmelt and into the disposition of the water released. These studies consisted of: (1) an intensive study of the snow disappearance from and about a forest clearing: (2) comparisons between north-facing and south-facing slopes with respect to snow disappearance and incident solar radiation; and (3) observations on soil moisture originating from snowmelt.

A. Snow disappearance from and about a forest clearing

A 42-acre clearing surrounded by forest was selected for this study. The clearing with its surroundings and the location of measuring instruments are shown in figure 35. Intensive mapping of the snow cover was performed on May 10, 15, 18, 20, 22, and 31, 1950, and supplemented by photographs taken from the top of the anemometer tower in the clearing. The six maps showing progressive snow disappearance are shown in figures 36 to 41. Figures 42 and 43 show for each of two dates the appearance of the snow cover as viewed in the four cardinal directions from the top of the tower in the open. The wasting of the snow cover from the clearing and surrounding forest, respectively, is presented in tabular form by table 6. While the snow in the clearing required about 30 days to disappear from beginning to end, that in the adjacent forest required about 37 days.

Table 6—Summary of snow-cover observations during May 1950 at windtower area

Date	Figure No.	Percentage of area covered by snow		Water equivalent, snow course in open (inches)	Percentage of area bare	
		In open	In forest		In open	In forest
April 1				16. 4		
May 3				11. 51		
10	36	95. 6	100. 0		4. 4	0
10				8. 54		
15	37	74. 9	100. 0		25. 1	0
17				1. 09		
18	38	38. 2	81. 0		61. 8	19. 0
20	39	24. 9	54. 0		75. 1	46. 0
22	40	7. 4	43. 0		92. 6	57. 0
24				0		
31	41	0. 7	22. 0		99. 3	78. 0

B. North-south slope comparisons

It is commonly observed that, even at high elevations, the snow on south-facing slopes disappears earlier than that on north-facing slopes. Differences in incident solar radiation are the obvious reason. However, detailed measurements of snow pack behavior and the relationships to incident radiation are few.

During the spring of 1950, such measurements were made on 60-percent (30 degree) north and south slopes facing each other across a narrow valley. Both slopes were forested although the forest density on the north-facing slope was considerably greater.

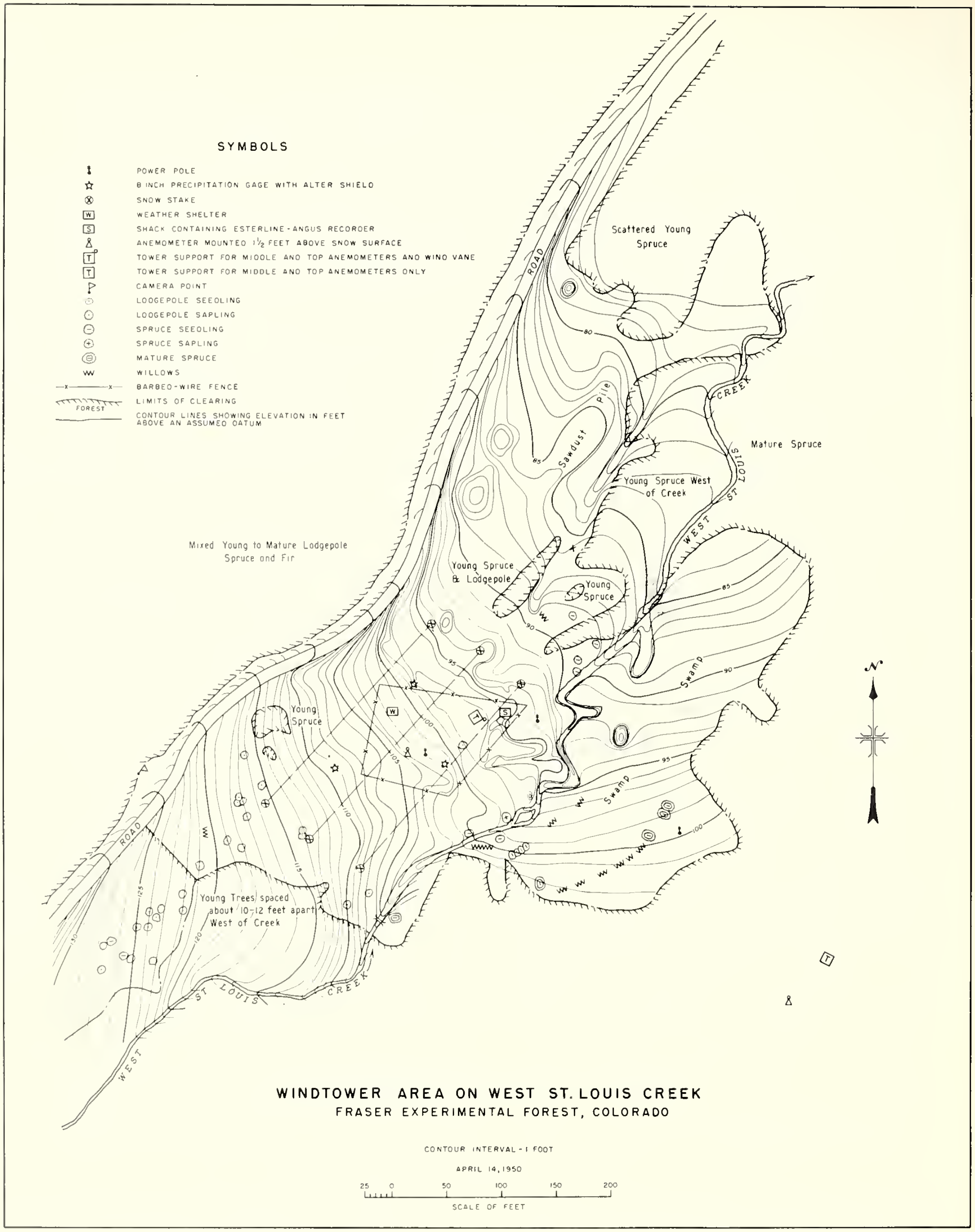


Figure 35. Topographic map of windtower area on West St. Louis Creek.

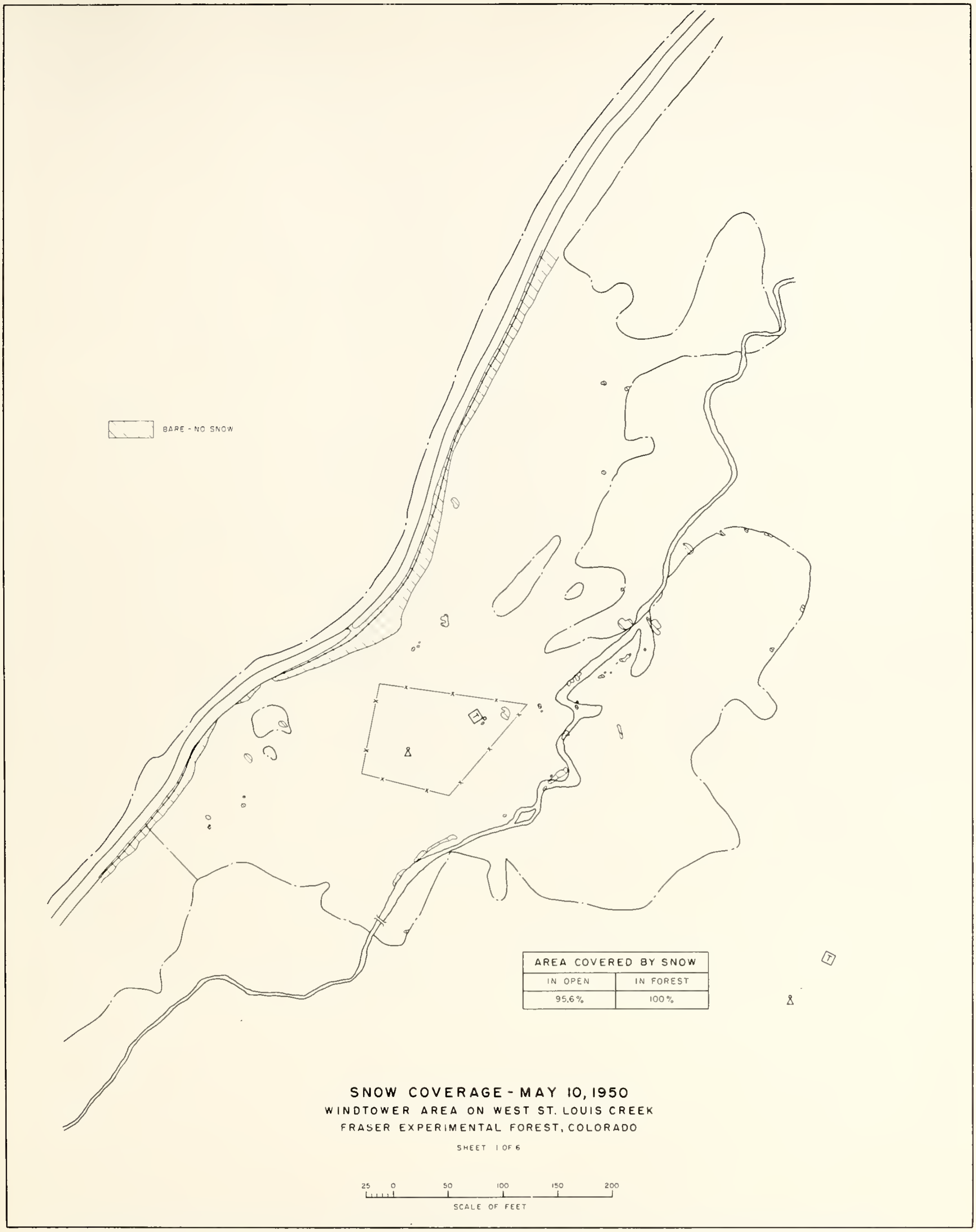


Figure 36. Windtower area on West St. Louis Creek showing snow coverage on May 10, 1950.

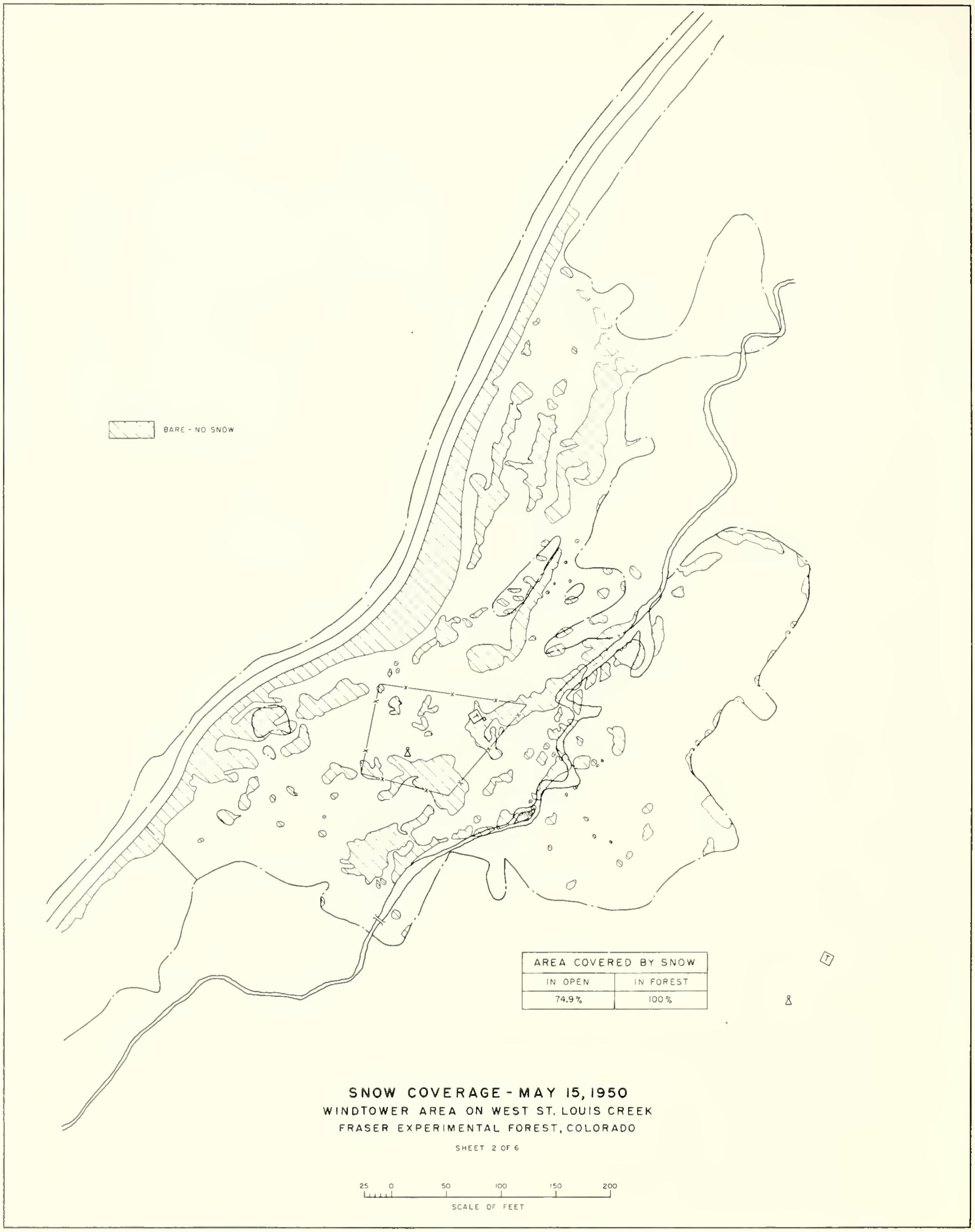


Figure 37. Windtower area on West St. Louis Creek showing snow coverage on May 15, 1950.

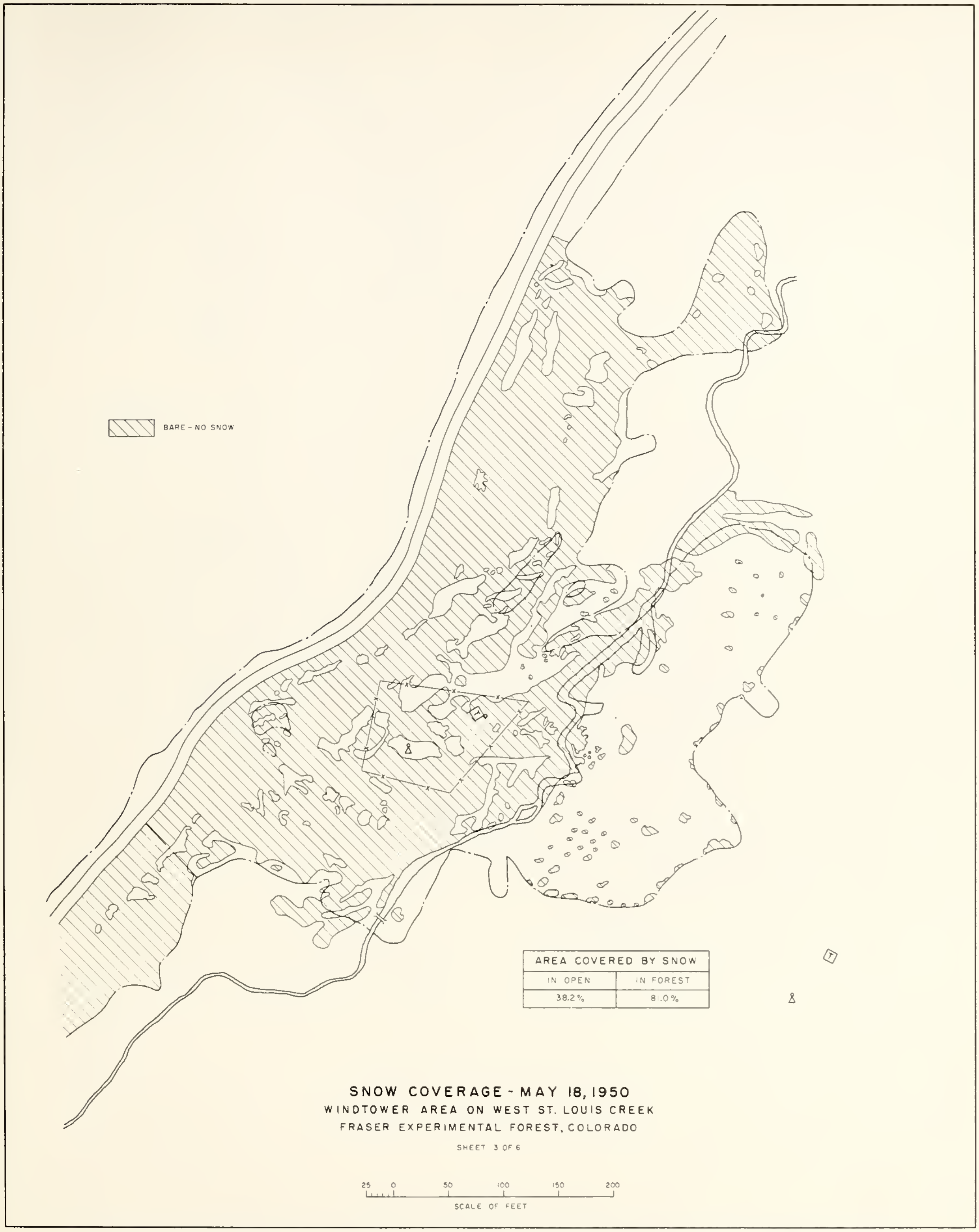


Figure 38. Windtower area on West St. Louis Creek showing snow coverage on May 18, 1950.

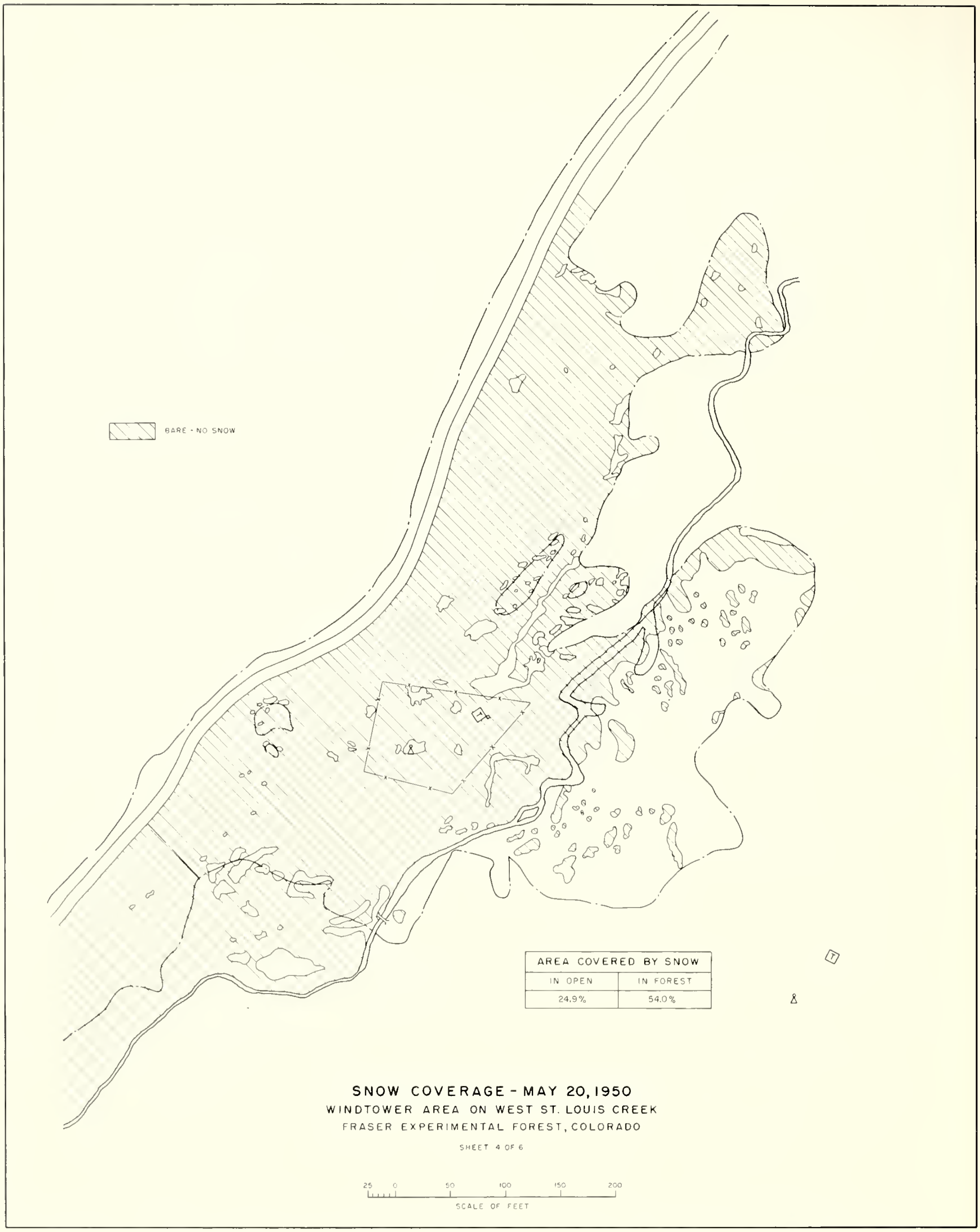


Figure 39. Windtower area on West St. Louis Creek showing snow coverage on May 20, 1950.

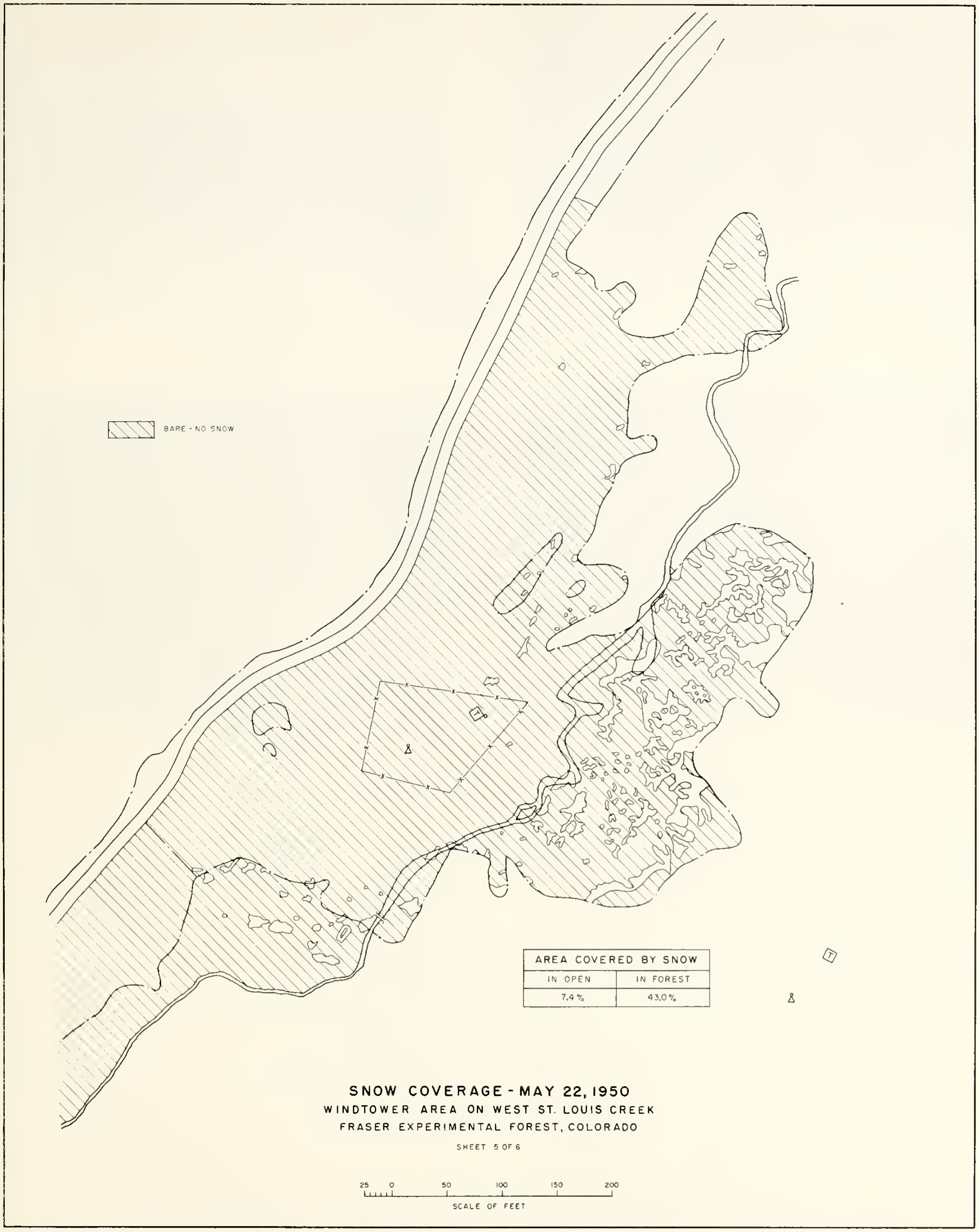


Figure 40. Windtower area on West St. Louis Creek showing snow coverage on May 22, 1950.

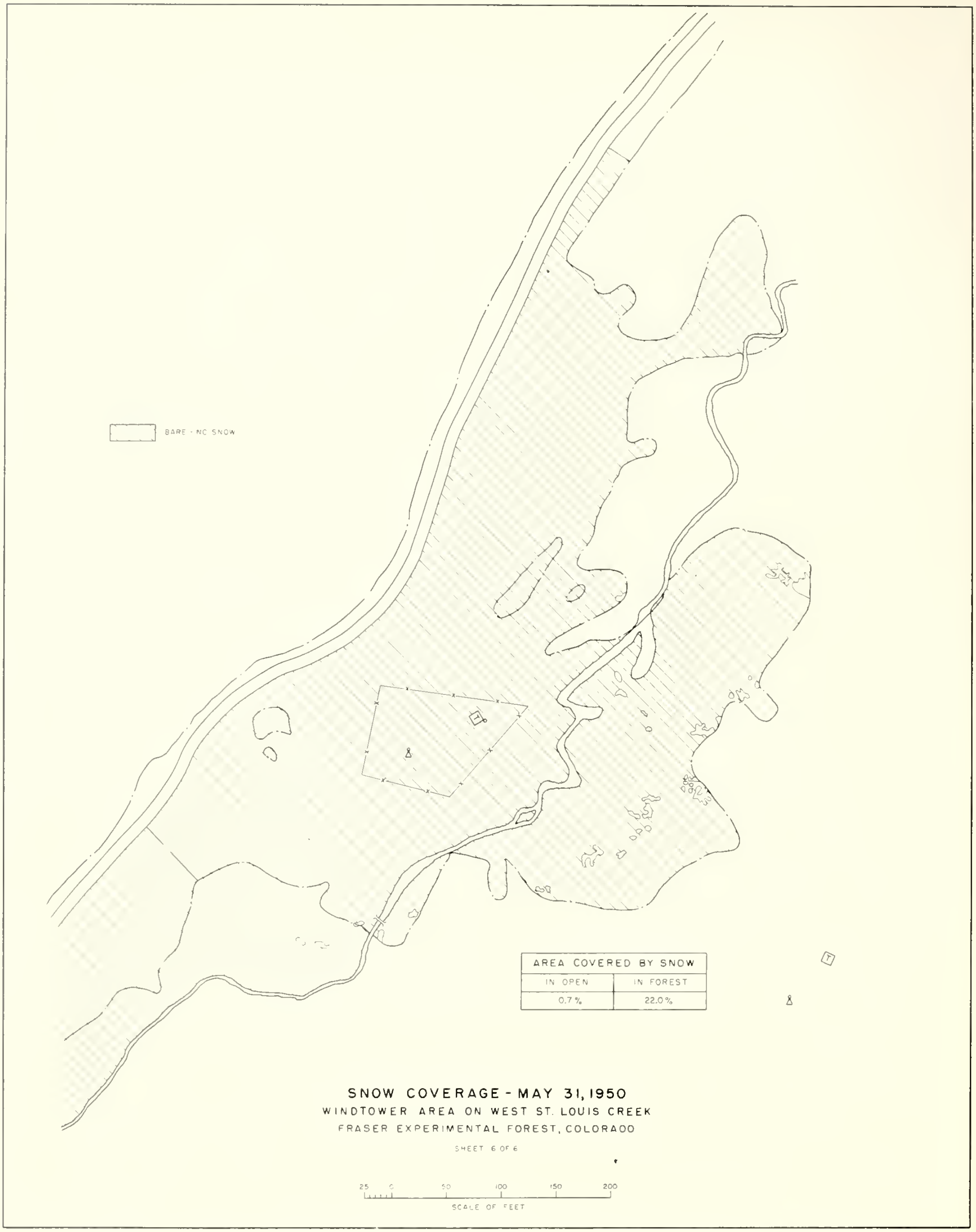
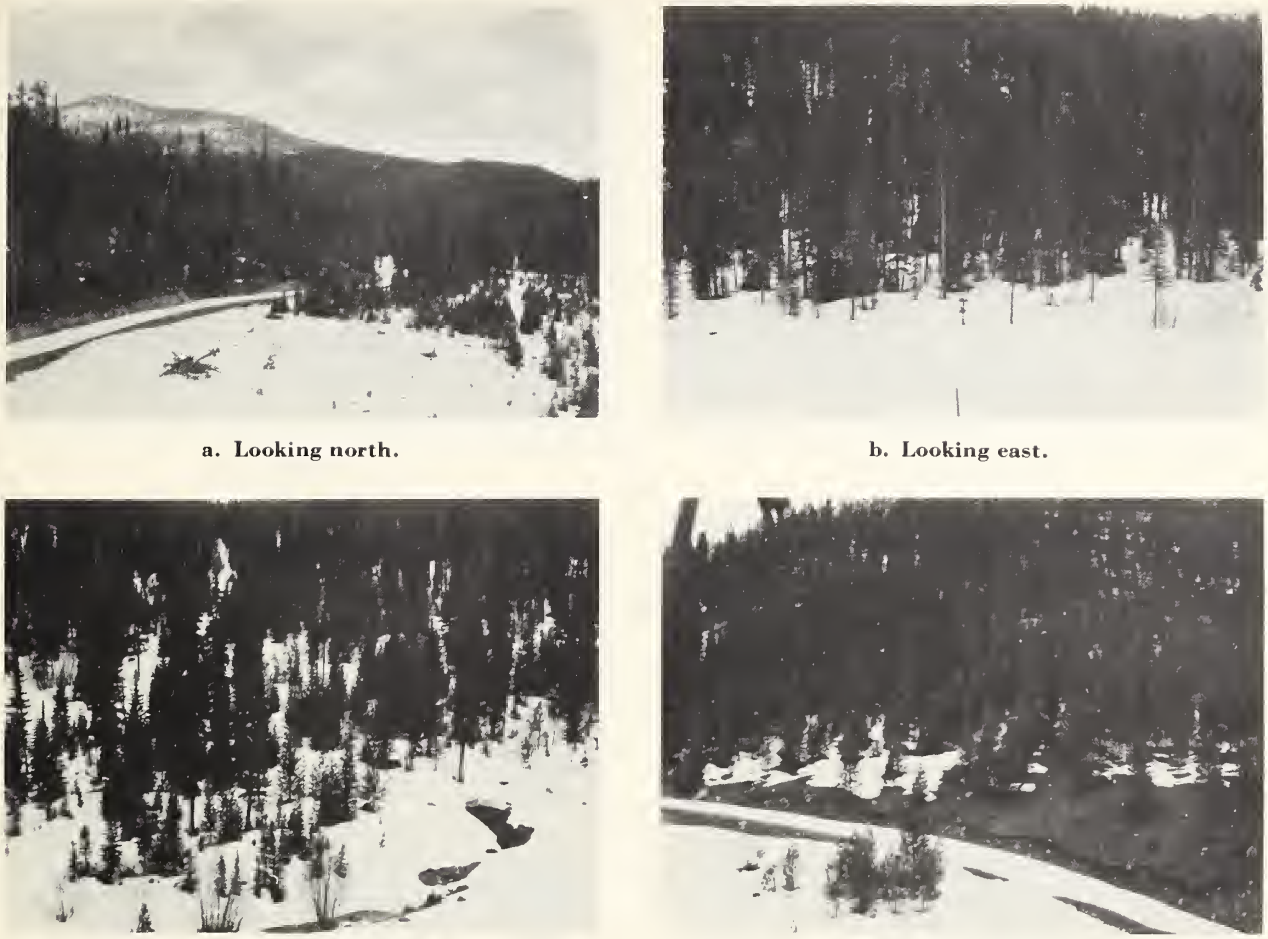


Figure 41. Windtower area on West St. Louis Creek showing snow coverage on May 31, 1950.



a. Looking north.

b. Looking east.

c. Looking south.

d. Looking west.

Figure 42. Snow cover on May 10, 1950, as viewed from the top of anemometer tower in clearing.

Similar views of the snow cover on the two slopes on two different days are presented in figures 44 and 45 which also show the differences in forest on the two slopes. Results from measurements on snow pack behavior are given in table 7.

From the measurements and observations the following conclusions were drawn:

a. At the beginning of the snowmelt season, the water equivalent of the snow pack on the north-facing slope was 12.1 percent greater than that on the south-facing slope.

b. The south slope lost its snow about 35 days before the north slope: May 17, as compared to June 22.

c. The time of most rapid melt on the south slope came 40 days before that on the north slope: April 26, as compared to June 5.

d. Snowmelt on the north-facing slope extended over 77 days; that on the south slope over but 46 days.

e. The steepness of the slope and the aspect were much more important in determining the rate of disappearance than was the elevation.

The relation of slope and aspect to incident solar radiation and consequent snowmelt is indicated by table 8. Relative values of incident radiation are presented for the four cardinal exposures, 60-percent slopes, and for two spring days. The days chosen are April 26 and June 5, when snowmelt rates were observed to be near or at their peaks on the sites used in this study. For comparative purposes, east and west slopes are presented along with north and south. All values are expressed as percentages of the radiation incident on the south slope and represent percentages of maximum possible sunshine as computed from relative positions of earth and sun on the sample days. The computational procedures are those of Byram and Jemison [18].

a. Looking north.

b. Looking east.

c. Looking south.

d. Looking west.

Figure 43. Snow cover on May 31, 1950, as viewed from top of anemometer tower in clearing.

Table 7—Summary of snow pack behavior on north and south slopes, 1950

Fraser Experimental Forest, Colorado

Date	Precipitation average increment		Average water in inches						Average depth		Average density	
			North slope			South slope						
	North slope	South slope	Snow pack	Difference	Melt [1]	Snow pack	Difference	Melt [1]	North slope	South slope	North slope	South slope
April 5	------	------	13.0	------	------	11.6	------	------	41.8	37.9	31.1	30.6
12	0.26	0.28	12.4	−0.60	0.86	9.1	−2.50	2.78	38.7	27.9	32.0	32.4
19	1.14	1.05	13.8	+1.40	[2] −0.26	8.0	−1.10	2.15	41.1	22.6	33.6	35.4
26	0.21	0.19	12.5	−1.30	1.51	3.8	−4.20	4.39	34.9	11.1	35.8	34.2
May 3	1.36	1.05	12.3	−0.20	1.56	2.1	−1.70	2.75	31.7	5.3	38.8	39.6
10	0.83	0.69	12.8	+0.50	0.33	1.2	−0.90	1.59	32.2	2.9	39.8	41.4
17	0.11	0.10	10.9	−1.90	2.01	0	−1.20	1.30	25.7	0	42.4	------
24	0.18	0.24	7.8	−3.10	3.28	0	------	------	18.6	0	41.9	------
31	1.35	1.43	7.8	0	1.35	0	------	------	18.1	0	43.1	------
June 7	0.86	0.95	3.1	−4.70	5.56	0	------	------	7.5	0	41.3	------
14	0.00	0.00	0.8	−2.30	2.30	0	------	------	1.8	0	44.4	------
22	0.08	0.03	0	−0.80	0.88	0	------	------	0	0	------	------
Total	6.57	6.13	------	−13.00	19.38	------	−11.60	14.96	------	------	424.2	213.6
Average	------	------	------	------	------	------	------	------	------	------	38.6	35.6

[1] Melt considered to equal precipitation increment minus weekly difference in snow pack.
[2] Experimental error. Theoretically should be equal to or more than 0.

a. North-facing slope.

b. South-facing slope.

Figure 44. Snow cover on 60 percent north- and south-facing slopes, April 12, 1950.

a. North-facing slope.

b. South-facing slope.

Figure 45. Snow cover on 60 percent north- and south-facing slopes, May 3, 1950.

Table 8—Relative values of incident solar radiation on different aspects, 1950

Date	Slope (percent)	Exposure			
		South (percent)	North (percent)	East (percent)	West (percent)
April 26	60	100	70	95	95
June 5	60	100	95	104	104

C. Soil moisture observations

A total of 24 pits were dug during the 1950 snowmelt season for the purpose of ascertaining soil moisture. About half of these pits were dug through a layer of snow. Six of these revealed a layer of soil carrying free water at an average depth of about 3 feet. The water-bearing layers were about 6 inches thick. In Pits 5 and 8, dug through the snow cover in late April, a layer of dry soil was found about 18 inches below the soil surface. Figure 46 is a photograph of Pit 8. This pit was dug in a large snow patch and revealed the following material from top to bottom: 22 inches of snow, 2 inches of frozen litter, 2 inches of frozen soil, 24 inches of dry soil, 12 inches of damp soil, 3 inches of water-bearing sand, and 11 inches of damp soil. In Pit 7, about 50 feet away, the water-bearing sand was only 30 inches below the surface.

The layer of dry soil in Pit 8 indicated the depth of penetration of water from directly overlying snow. The water in the wet soil below the dry layer was judged to have followed a porous stratum after deep penetration beneath snow lying uphill from the point of observation. Subsequent visits to the pits in early May indicated that the snow water had penetrated the dry layer.

The results of the soil moisture observations are summarized in appendix B. Further evidence

Figure 46. Digging test pit No. 8 in the middle of a snow patch near the lower portion of a hill just north of the headquarters building. April 25, 1950.

of subsurface flow was observed in sidehill road cuts, one of which is shown in figure 47.

D. Snow disappearance and streamflow

Studies of the relation between the snow disappearance and streamflow from watersheds have been reported by several authors. An early use of snow cover photographs in runoff forecasting is described by Potts [78]. Other investigations are described or discussed by Daniels [29], Miller [72], and Garstka [39]. Kaitera [58] discusses the progress of spring snowmelt in Finland and presents the following material: [5]

Summary of melt season progression in Finland

Number of days from beginning of snowmelt	*Percent of maximum snow-water equivalent melted*
0	0
5	45–50
10	70
15	85
30	95

[5] Reference 58, page 38.

Figure 47. Snowmelt water discharging from road cut 10 feet below ground surface. June 16, 1950.

Kaitera further states: [6]

Notwithstanding that the absolute values (stated in mm) are varying considerably owing to the snow volume, the approximate values in different parts of the country under different topographical conditions will be rather close to the above-stated figures. The melting maximum will occur some days later in the woods than on the fields, and similar variations will also be ascertained depending on the fact whether a slope is facing south, north, west, or east.

The present study was made during the spring of 1950 on the 32.8-square-mile area of St. Louis Creek from which the streamflow is gaged. Snow observations were begun in early April to note the appearance of bare ground. When the extent of such areas became appreciable in early May, the subsequent development was recorded by maps and photographs until July 12, when practically all snow had disappeared.

The mapping was effected by observation through binoculars from three high-elevation points that, in combination, permitted a view of the entire basin. Observations were systematized by delineating tributary basins on a base map of scale 3.13 inches per mile prepared from aerial photographs. The tributary areas were further subdivided into indexed compartments (figure 48) to facilitate recording observations in note form. The snow cover on each compartment was estimated and recorded to the nearest 5 percent. The final step was to enter on a map overlay the percentages of snow cover in all compartments and, by introducing compartment areas, arrive at a snow cover percentage for the whole watershed. (Brown and Dunford [17].)

[6] *Ibid.*

Observations were made at weekly intervals except when storms blanketed the area with new snow and necessitated brief delays to allow the pattern of the winter pack to reappear. A total of 15 maps was prepared of the snow pattern and the maps were periodically supplemented by panoramic series of photographs. Two of these photographic series portraying the snow pack disappearance are presented as figures 49 and 50.

Before April 1, the entire watershed was snow covered except for areas too steep to hold snow or so exposed that wind kept them blown clear.

The first areal disappearance of snow due to melting started in early April at the lowest elevations on south aspects. Snow disappearance

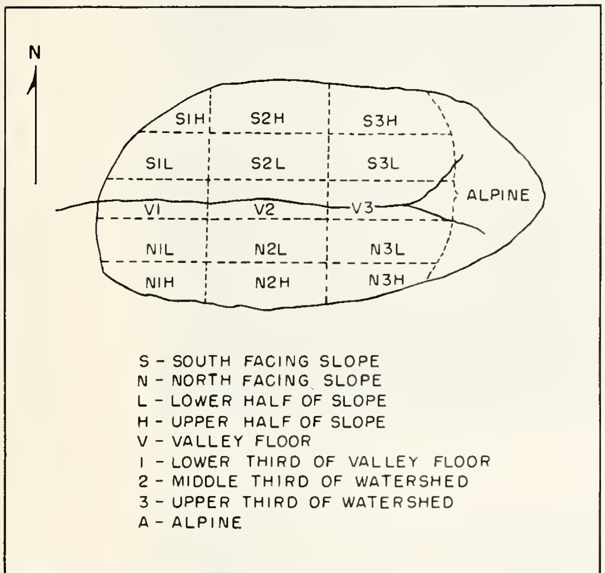


Figure 48. Method of dividing tributary watersheds into topographic compartments to record snow cover.

was limited to those sites until the middle of May. From then until mid-June, extensive bare areas appeared on north slopes at low elevations and on south aspects at high elevations. Snow on east and west aspects disappeared after that on the south but before that on the north aspect. In the latter part of June, snow disappeared from north aspects at high elevations and from those alpine areas without deep drifts. By mid-July, the only snow remaining was in deep alpine drifts such as those in the steep cirques at the head of each major drainage. A few drifts persisted throughout the summer. The following series of figures consists of maps showing the average snow cover on the designated dates: figure 51, May 9, 1950, 92-percent snow cover; figure 52, June 6, 1950, 70 percent; figure 53, June 13, 1950, 49 percent; figure 54, June 20, 1950, 36 percent; and figure 55, June 26, 1950, 19-percent snow cover. Figure 56 is a composite chart consisting of a hydrograph of the 1950 snowmelt season of St. Louis Creek into which have been inserted the precedingly enumerated five figures showing the snow coverage in relation to streamflow.

A significant result of this snow disappearance study is the finding of the close relation which exists between streamflow and snow-cover depletion. This relation is shown in figures 57 and 58. Figure 57 covers the period April 1 through July 31, since that is the most commonly used period for seasonal water-yield forecasting of volumes of flow, and consists of three curves: one is the snow-cover depletion curve, depicting the percentage of area which is bare on given dates; another is a curve of streamflow accumulation as measured at the St. Louis Creek gaging station; and the third is a volume accumulation curve including the recession contribution to the snowmelt hydrograph in percent of the April through July 31 total.

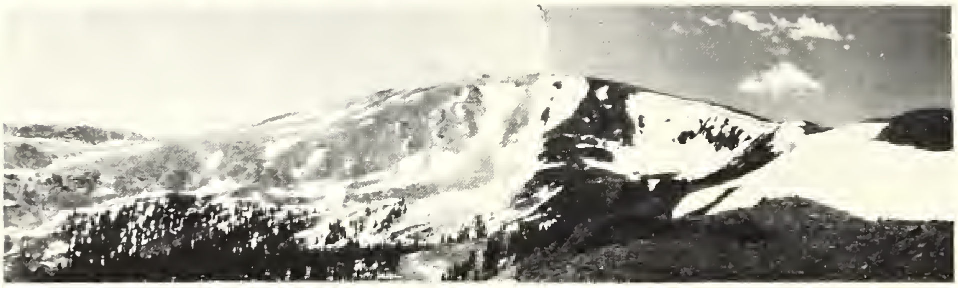
The streamflow accumulation curve is consistently below the snow-cover depletion curve by an increasing amount near the first of July, indicating that the snow cover disappears before snowmelt water appears as runoff. This evidences the effect of the retention of water by the soil and also of the time lag associated with the flow of water through the ground to the stream. It will also be noted that the point of steepest slope on the streamflow accumulation curve, which is the day of peak flow, June 17, 1950, occurred when about 45 percent of the basin was still covered with snow.

The volume of runoff in the volume-accumulation curve was computed by a method which is described in detail in section 7. The volume-accumulation curve rises above the snow-cover depletion curve on May 15, indicating that early in the melt season the average water-equivalent depth of the snow cover decreases faster than the change in area.

The volume-accumulation curve breaks sharply between July 15 and 20, simultaneous with the occurrence of the peak rate of discharge, after which the curve continues at a much flatter rate. This indicates that, although there was from 35 to 45 percent snow cover during the period June 15 to 20, the water yield from this area was no

June 2

June 19



June 26

July 3

[illegible]

Figure 49. Snow disappearance in upper Range Creek Basin, a tributary of St. Louis Creek, 1950.

June 2

June 12

June 19

June 26

July 12

Figure 50. Snow disappearance in western portion of St. Louis Creek drainage. Byers Peak is prominent on far right. Iron Creek Valley is at left. 1950.

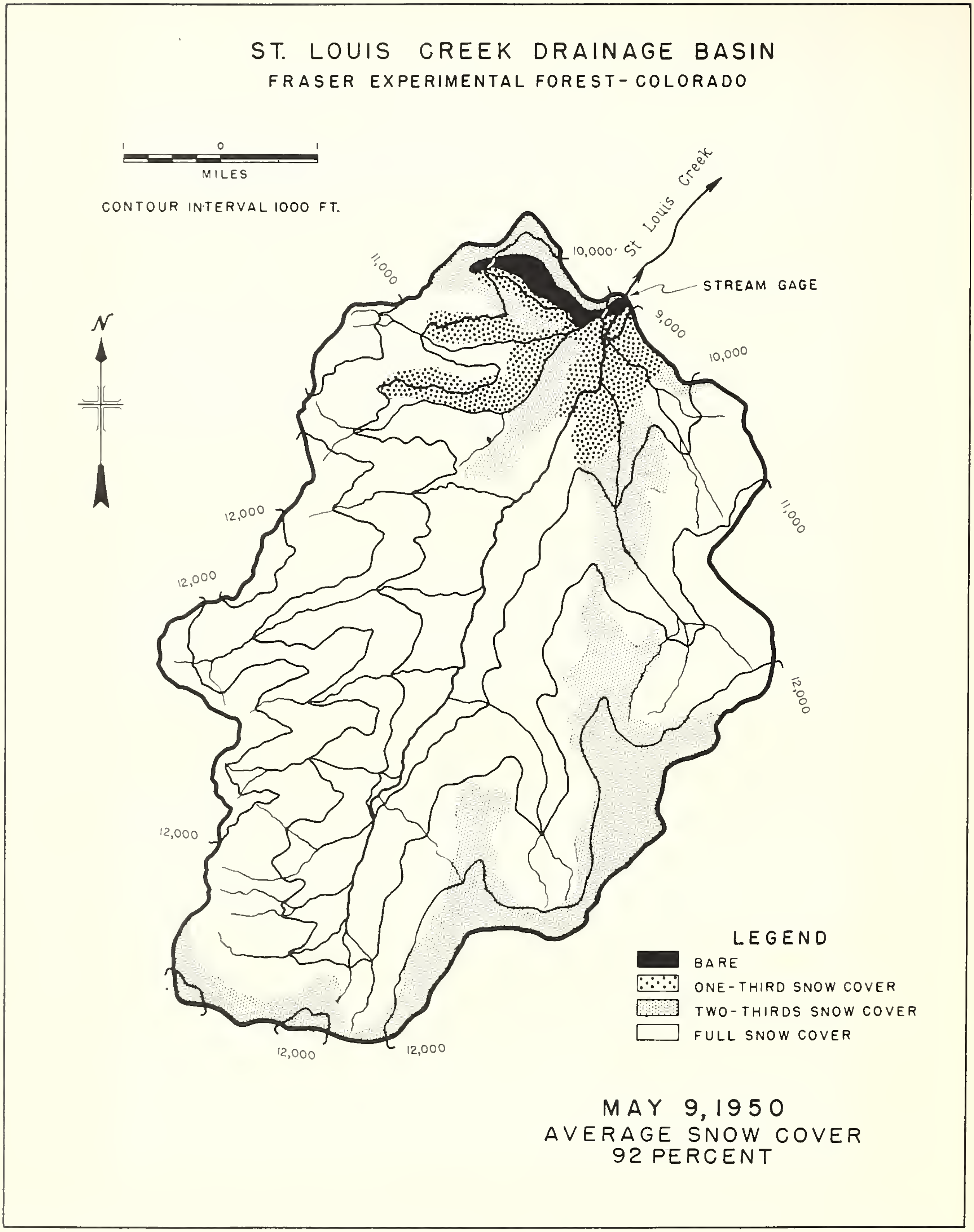


Figure 51. Snow cover on May 9, 1950.

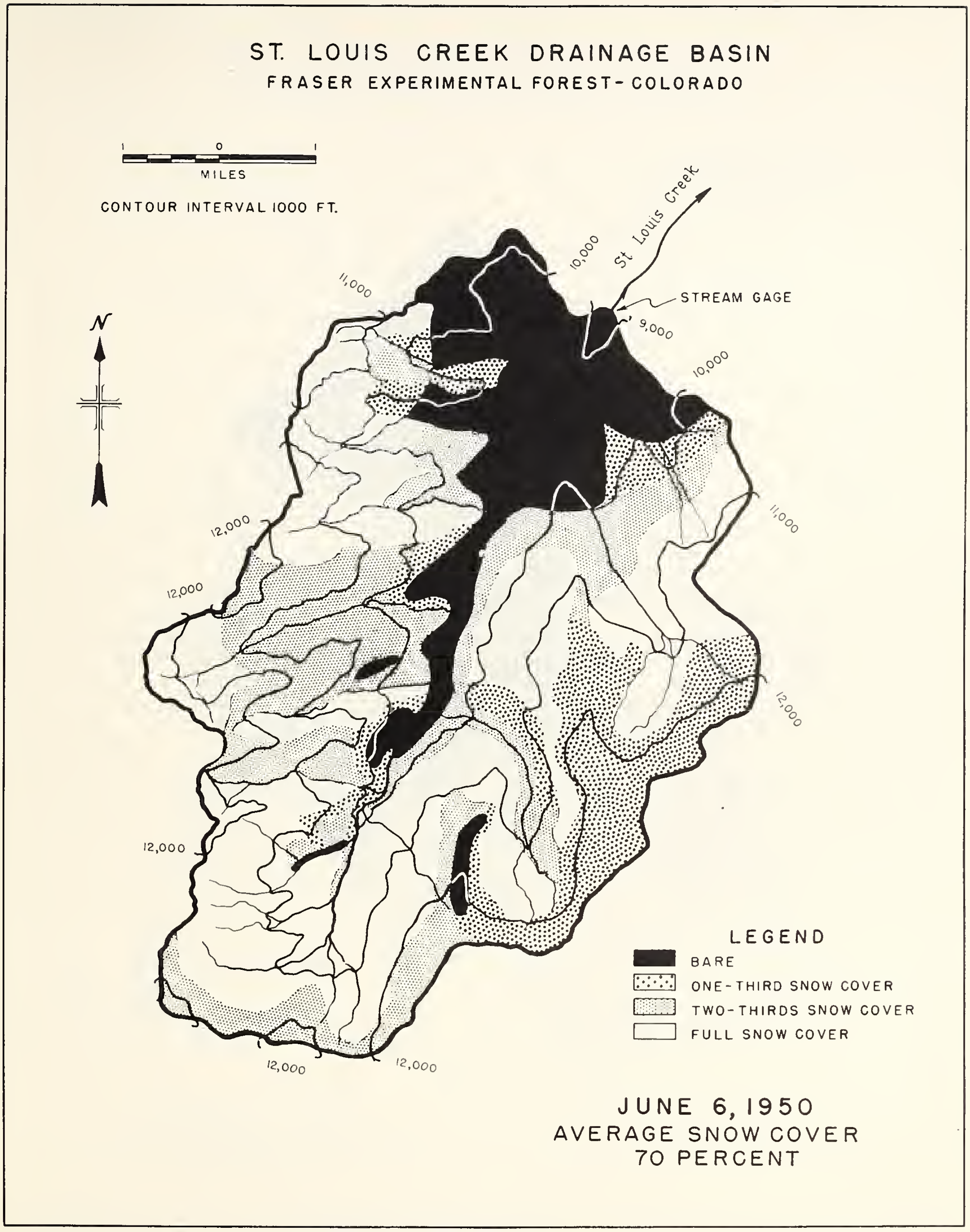


Figure 52. Snow cover on June 6, 1950.

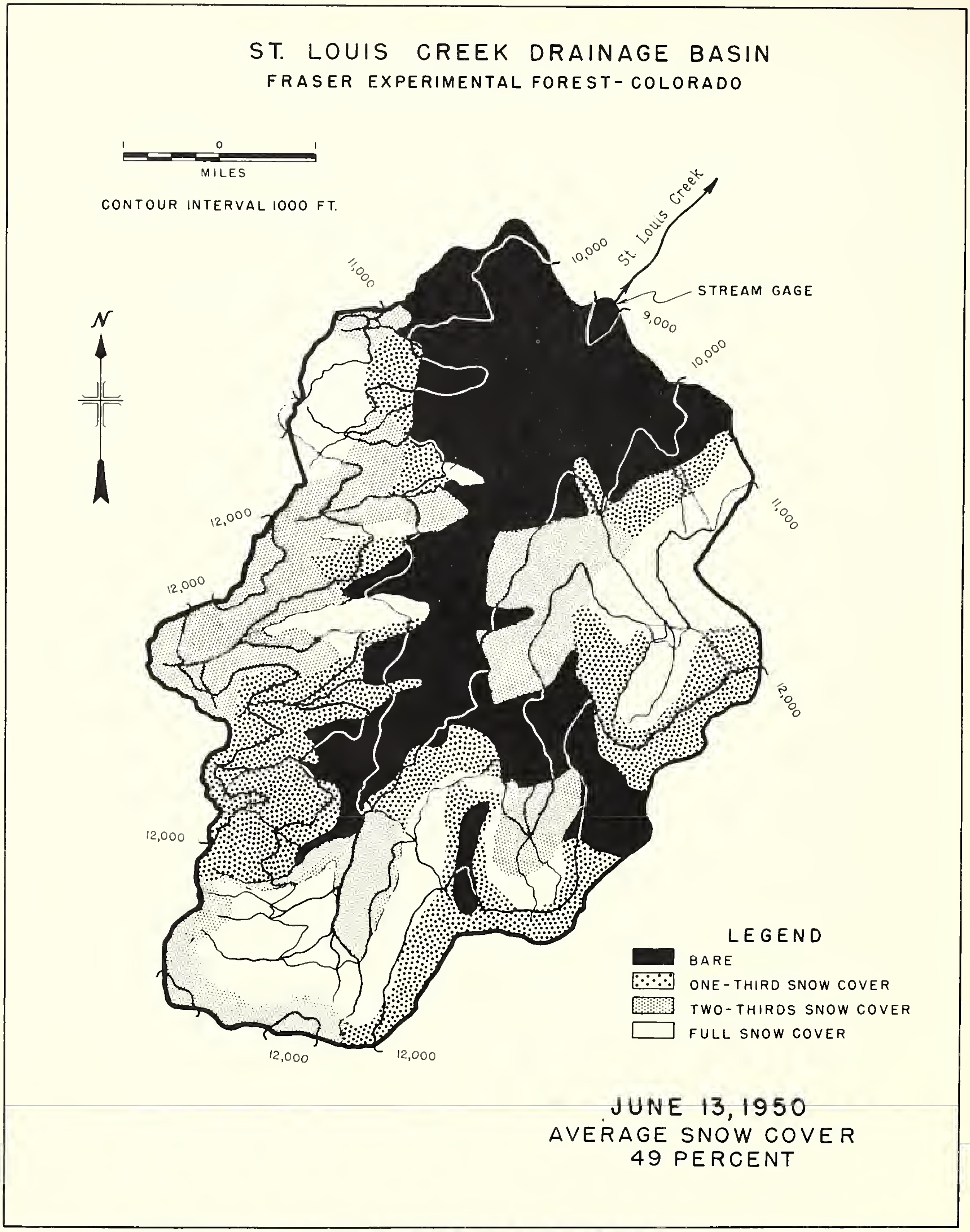


Figure 53. Snow cover on June 13, 1950.

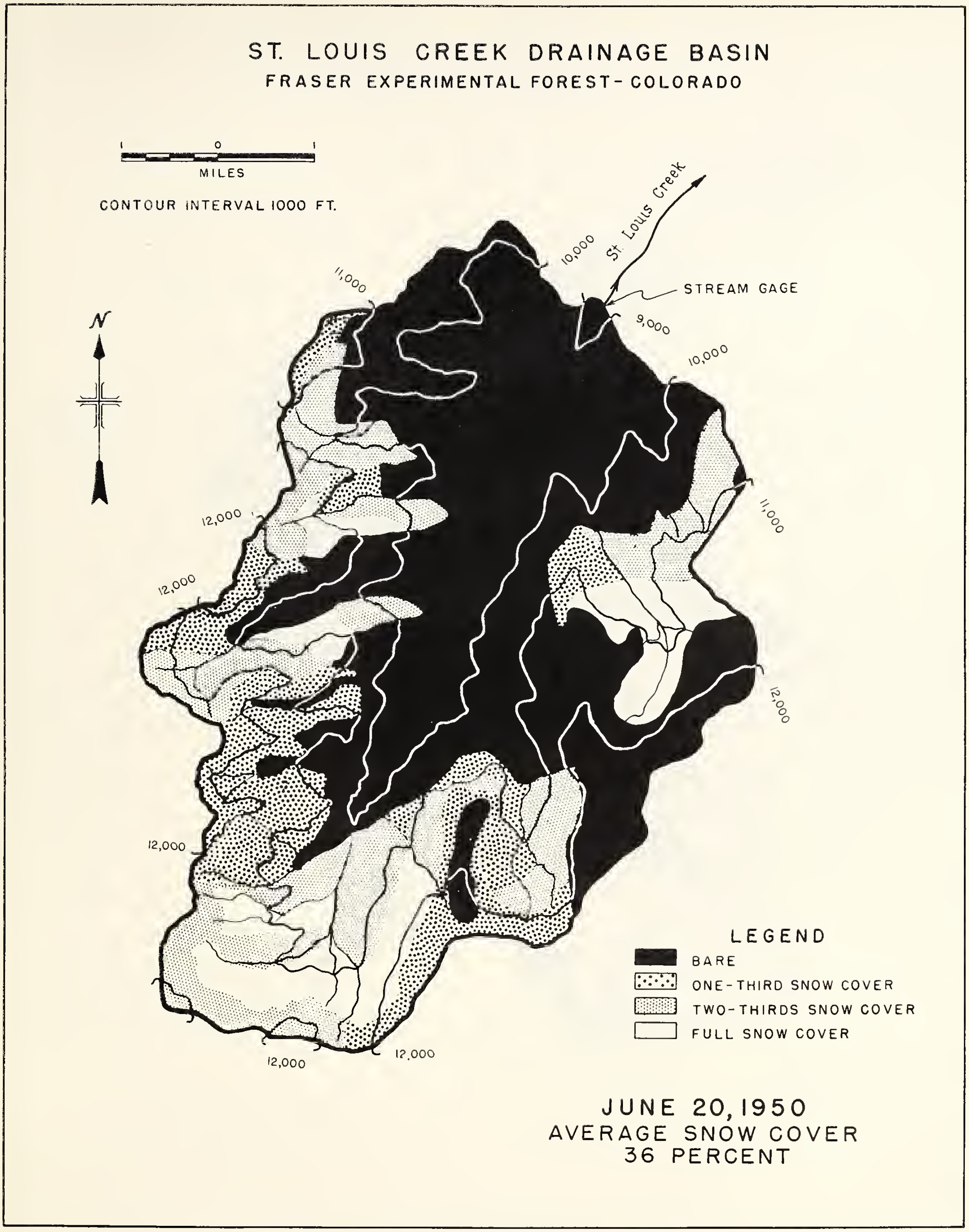


Figure 54. Snow cover on June 20, 1950.

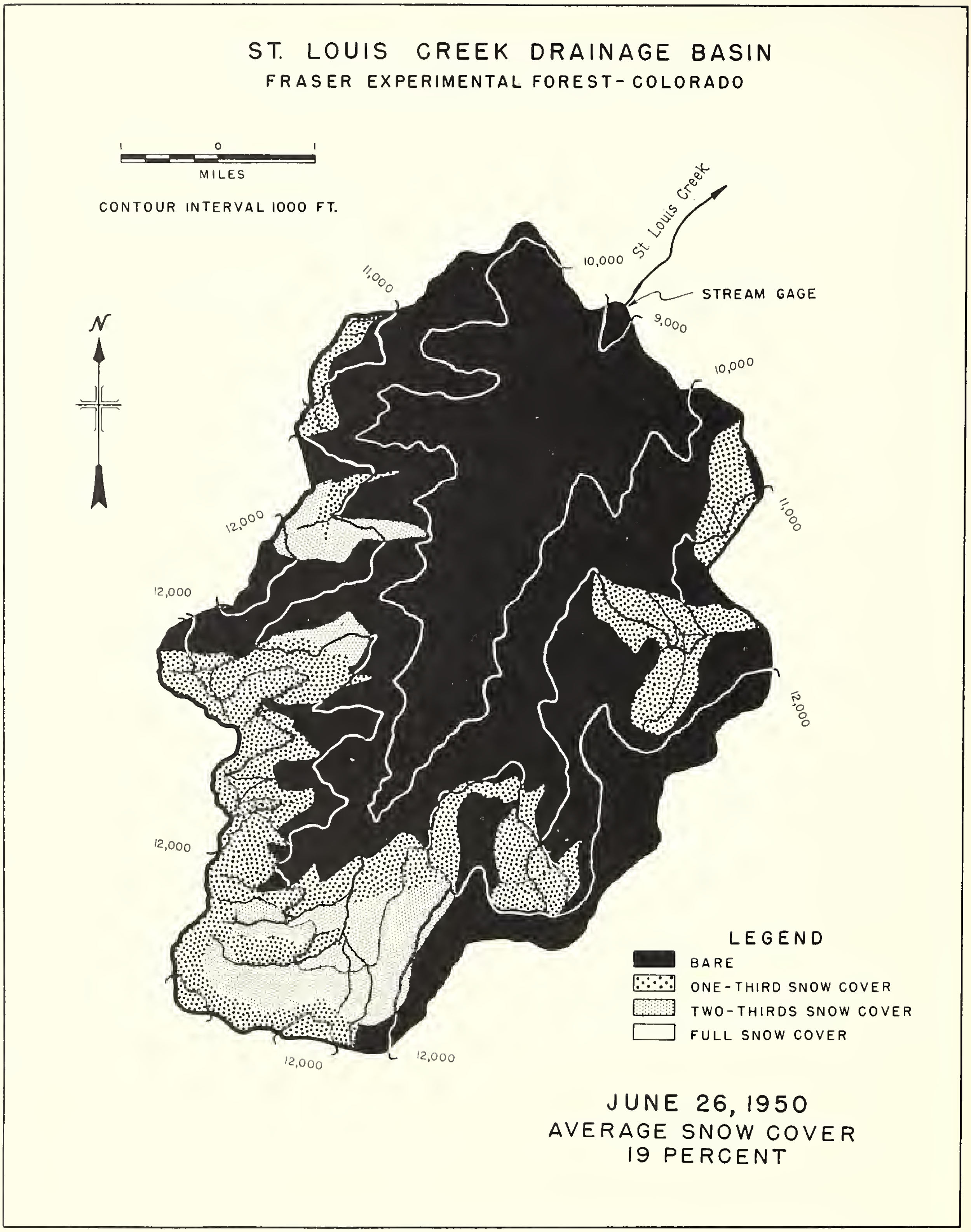


Figure 55. Snow cover on June 26, 1950.

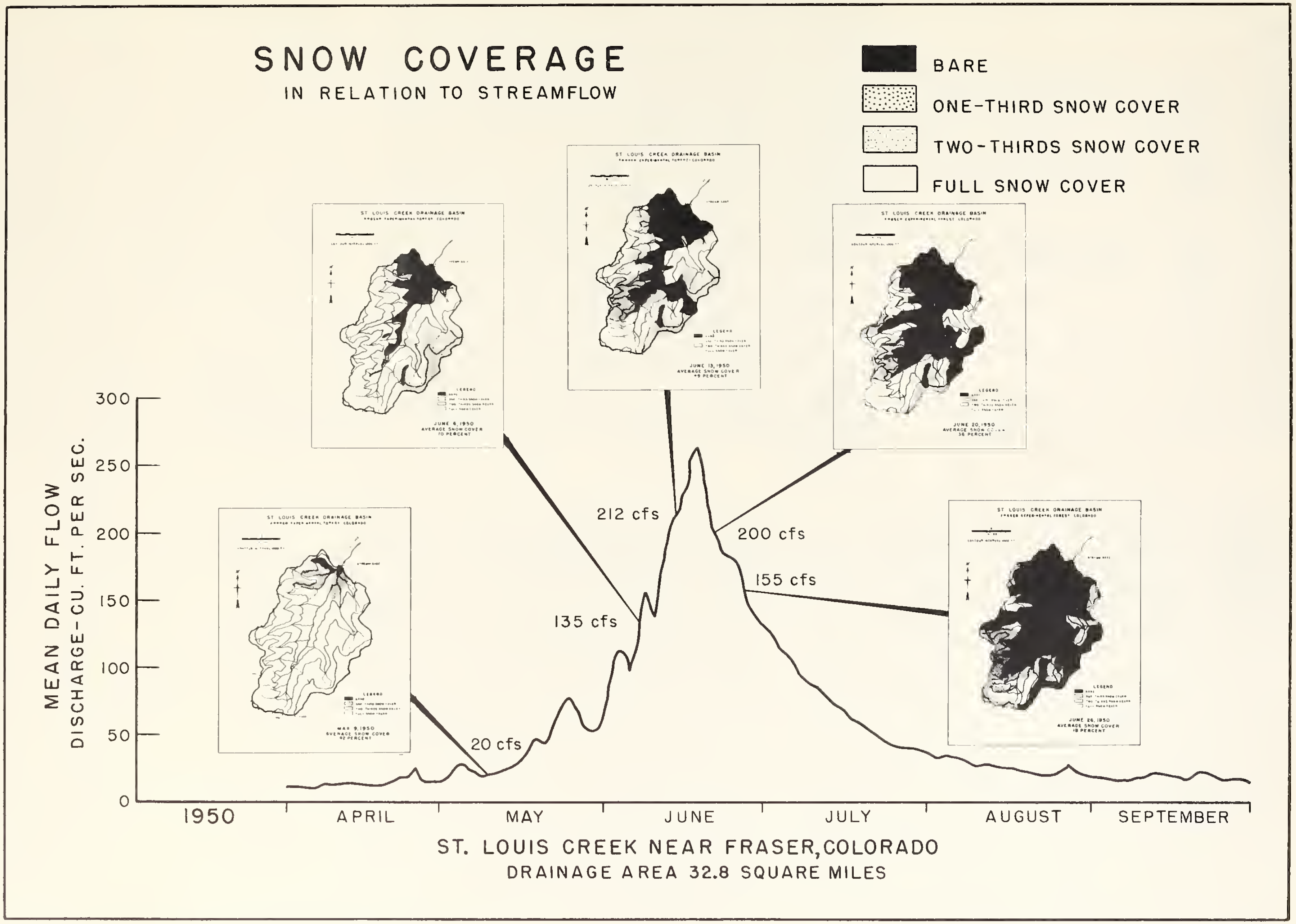


Figure 56. Snow cover in relation to streamflow, 1950.

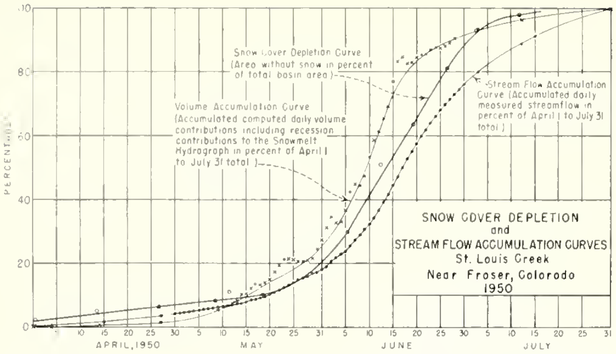


Figure 57. Snow cover depletion and streamflow accumulation curves for period April 1 to July 31, 1950.

Table 9—Area of snow cover and discharge during the period April 1 to July 12, 1950

St. Louis Creek, Fraser Experimental Forest, Colorado

Date	Area of snow cover (percent)	Mean daily discharge (c. f. s.)	Cumulative discharge (acre-feet)	Figure No.
April 1	97. 7	9	17	
4	100. 0	9	70	
14	94. 9	12	286	
27	93. 5	12	642	
May 9	91. 7	20	1, 089	51
12	89. 2	23	1, 212	
19	90. 0	42	1, 693	
June 6	70. 1	135	4, 437	52
13	49. 2	212	6, 817	53
20	36. 3	200	10, 082	54
27	18. 7	145	12, 480	55
July 3	7. 2	113	13, 965	
12	2. 1	74	15, 553	

longer sufficient to offset the decreased ground water discharge from areas earlier freed of snow.

Figure 58 presents data similar to those of figure 57, but includes only the cumulative discharge curve for the period through July 12, at which time the drainage basin was nearly devoid of snow.

A comparison of the snow disappearance in relation to streamflow can be seen from the beginning of April through July 12, by the data presented in table 9, the table of areal snow cover and discharge during the snowmelt period. In early April, the snow cover was nearly complete and St. Louis Creek was flowing at its base level of about 9 c. f. s. As the first bare areas appeared at low elevation, the stream started a gradual rise. Both the bare area and streamflow increased slowly until about May 19, when the bare area totaled about 10 percent of the basin and the daily discharge averaged about 42 c. f. s. Then the snow began to disappear more rapidly, about 30 percent of the area of the drainage basin being bare by early June. During this period of moderate melt, the rate of discharge fluctuated widely but made an overall rise to an average of about 135 c. f. s. After June 6, the rate of snow disappearance was consistently high until July 3, at which time most of the snow was gone from the drainage basin.

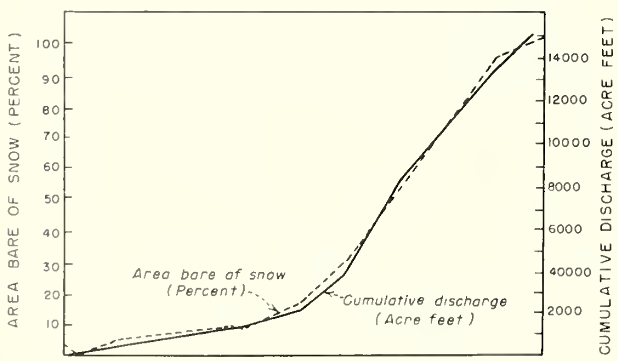


Figure 58. Snow cover depletion and streamflow accumulation curves for period April 1 to July 12, 1950.

During this relatively short period, which was roughly one-fourth of the melt period, 63 percent of the watershed lost its snow cover and 57 percent of the cumulative discharge was recorded through July 12 at the stream gaging station. It was during this period, on June 17, that the peak daily rate of discharge, 293 c. f. s., was reached.

On June 27, 81 percent of the watershed was bare of snow, and practically all of the snow below the 10,000-foot elevation had melted. After July 3, the snow disappearance rate dropped off quickly since, by that time, only the snow remaining on the sheltered sites at high elevations was in evidence, and the cumulative discharge began to level off at the same time for reasons previously mentioned.

Table 10 presents the information of table 9 in different form. Here the increase in bare area is compared with the percent of cumulative discharge of St. Louis Creek for the period April 1 to July 12.

E. Relation of areal and volumetric snow-cover disappearances

The volume of water in the snow pack for St. Louis Creek Drainage Basin was estimated from five snow courses in the drainage basin. Ten samples were taken at each course on March 30, April 30, and June 2. The measurements were averaged for each date and expressed as a percentage of the

Table 10—Relation between bare area and accumulated streamflow for the period April 1 to July 12, 1950

Date	Portion of watershed bare of snow (percent)	Cumulative discharge (percent)
April 1	2. 3	0. 1
4	0. 0	0. 4
14	5. 1	1. 8
27	6. 5	4. 1
May 9	8. 3	7. 0
12	10. 8	7. 8
19	10. 0	10. 9
June 6	29. 9	28. 5
13	50. 8	43. 8
20	63. 7	64. 8
27	81. 3	80. 2
July 3	92. 8	89. 8
12	97. 9	100. 0

March 30 value. Figure 59 presents a comparison between these percentages and the percent of the areal snow cover for the drainage basin. Comparisons among this figure and figures 57 and 58 indicate that the areal extent of snow cover is more closely related to the melt period streamflow than is the current water content of snow.

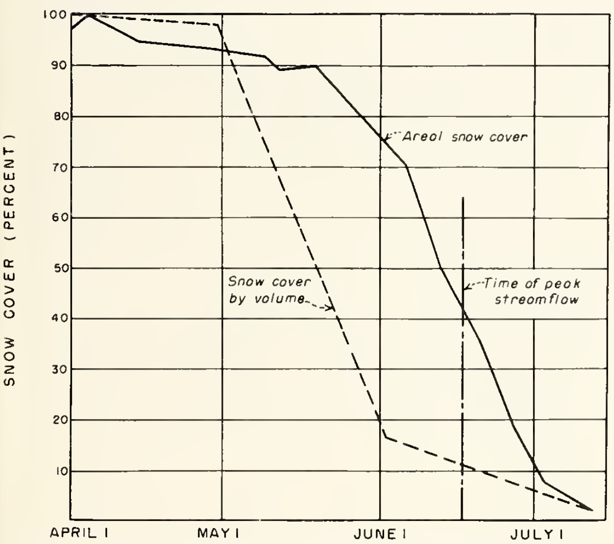


Figure 59. Relation between volume of snow cover and area of snow cover for period April 1 to July 12, 1950.

The initial spring rise of St. Louis Creek in 1950 was delayed several weeks from the time snowmelt began, but it corresponded rather closely with the first appearance of bare ground in the drainage basin. The general snow disappearance study indicated that there is a lag of about 20 days between the first snowmelt and the first general rise of the hydrograph for the snowmelt season. At the start of the snowmelt season, 98 percent of the area was covered with snow which contained practically 100 percent of its maximum snow-water equivalent for the 1950 season, whereas, at the date of the peak of the snowmelt runoff, the area of snow cover was only 40 percent and the volume of the snow-water equivalent remaining in the drainage basin was about 10 percent of that of the maximum for this snowmelt season.

F. Summary

Although this study was made for only one year, it does indicate the possibilities of establishing a reliable basis for making short-term streamflow forecasts based on the extent of snow cover as the prime index. Obviously, observations should be made for several years for any firm relation to be established. However, the general agreement between the watershed area bare of snow and the percentage of total melt-period discharge indicates the possibility of estimating the streamflow during the snowmelt period on the basis of proportion of bare area.

Figure 60 is a summary of the 1950 snow disappearance. This chart depicts maximum and minimum air temperatures at the headquarters station, wind travel at the headquarters station, precipitation at the headquarters station, precipitation at West St. Louis Creek windtower site, the water equivalent of snow on the ground of the West St. Louis windtower site, the precipitation and the water equivalent of snows on the north and south facing slopes at the study area on the West St. Louis Creek and the hydrographs for St. Louis Creek, East St. Louis Creek, and Fool Creek.

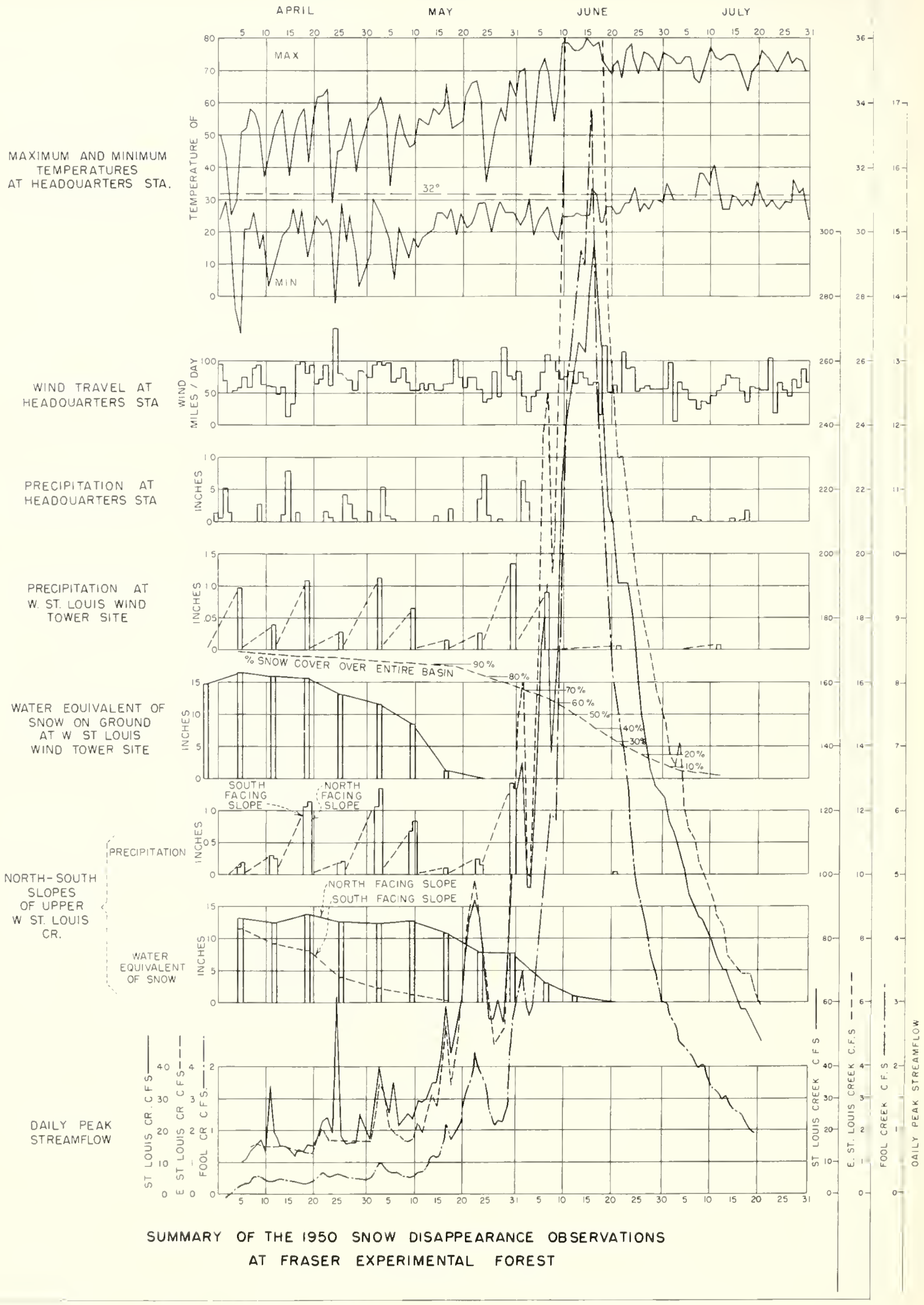


Figure 60. Summary of the 1950 snow disappearance observations.

SECTION 7—RECESSION ANALYSES

A. General

An investigation of the processes of snowmelt runoff consists of two broad subjects: (a) A determination of the amount of heat available for the melting of snow, and (b) a determination of the amount of runoff yielded by the melting of snow under the influence of a recognized amount of heat. The need for a method of segregating a given day's snowmelt contribution to runoff was recognized long ago, since without such segregation correlation of snowmelt runoff with heat was practically unattainable. This section describes the analyses made of snowmelt hydrographs in the Fraser Experimental Forest.

For the purposes of this study, the following modifications of definitions by C. R. Hursh [55] have been adopted:

Surface runoff.—That portion of the snowmelt water which is induced by gravity to move over the surface of the ground and into the drainage channels.

Subsurface runoff.—That portion of the snowmelt water which infiltrates into the surface soil but moves away from the area and into the drainage channels through the upper soil horizons at a rate much in excess of normal ground-water flow.

Ground-water flow.—That portion of the snowmelt water which has been absorbed by the ground and has become part of the ground water, ultimately being discharged as spring and seepage water into the stream channels.

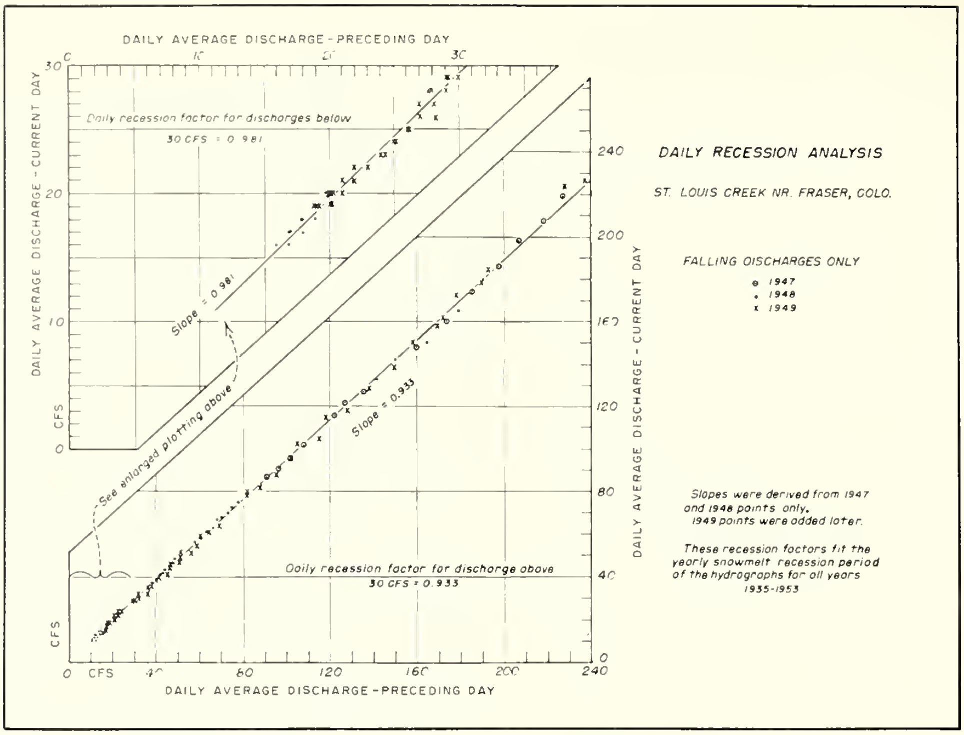
This analysis of the snowmelt hydrograph is based upon field experience in observing watershed runoff from snowmelt. In forested watersheds there is, in effect, no watershed-wide surface runoff from snowmelt. Practically all of the snowmelt runoff enters stream channels as subsurface or ground-water flow, usually as a combination of both. It was reasoned, therefore, that the hydrograph recession of the end of the snowmelt season should apply to each day's snowmelt contribution to the total flow, as the runoff is a Darcy's law summation of the individual day's contributions of discharge of water through a porous medium, rather than the summation of overland hydraulic flows.

B. Selection of recession factors

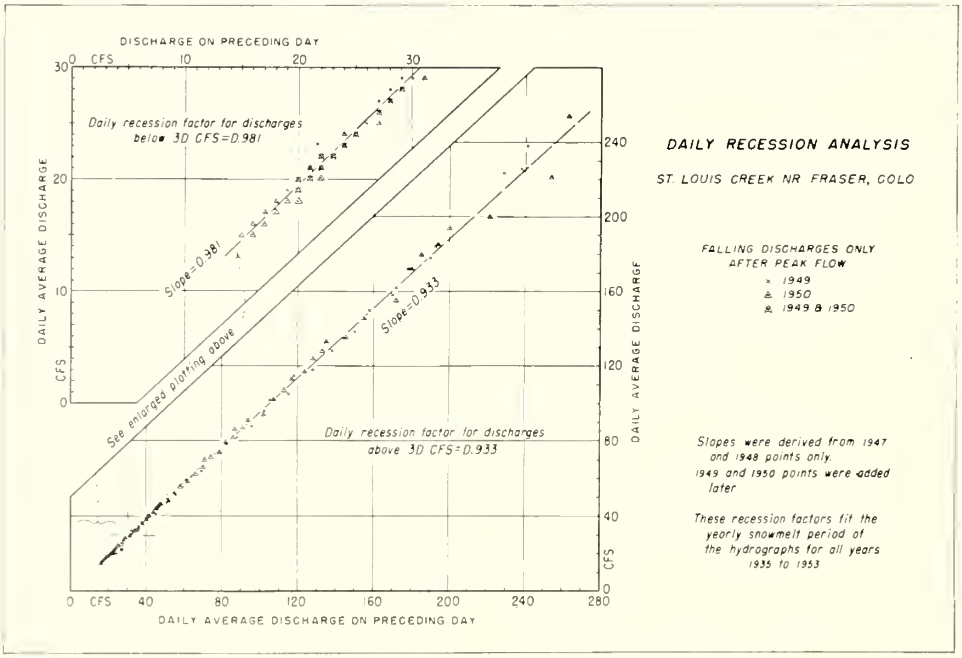
Hydrograph recession factors were derived from the 1947 and 1948 seasons as follows. Daily average recession discharges in c. f. s. of St. Louis Creek near Fraser, Colo. (drainage basin area 32.8 square miles), were plotted against the daily average discharges on the preceding day for the 1947 and 1948 snowmelt seasons only for those days uninfluenced by rain. A recession factor was determined by deriving the slopes of the lines, as shown in figure 61A. The daily recession factors, as computed from this plotting, were found to be 0.933 for flows above 30 c. f. s. and 0.981 for flows below 30 c. f. s. When 1949 and 1950 data were added, as shown on figure 61B, their recession points fell on the line just as well as did the 1947–48 points. The recession values of 0.933 and 0.981 were also found to fit the hydrographs of St. Louis Creek for the period 1935 through 1953, inclusive. (See hydrographs on figures 9 to 12). The resulting recession curve is shown on figure 62.

Figure 63 is a plotting of the hydrograph for the 1949 snowmelt season on semilogarithmic paper. This type of plotting, according to Barnes [7], is advantageous in disclosing recession characteristics of hydrographs. The recession values of 0.933 and 0.981 have been plotted as derived from figure 61 on figure 62, and serve to illustrate the manner of interpreting a semilogarithmic plotting. The value of the recession coefficient, as derived, will be the same as derived by either arithmetic or semilogarithmic graphical treatment.

In this series of analyses, a winter flow of 8 c. f. s. and below was considered as a ground-water base flow, above which contribution of individual day's snowmelt could be segregated. For flows at 8 c. f. s. and below, it was not considered practical to attempt to segregate an individual day's snowmelt contribution to the ground-water flow, as de-



a. Derivation, using data from 1947 and 1948.



b. Check of recession slopes derived from 1947–48 data with observed 1949–50 flows.

Figure 61. Daily recession analysis, St. Louis Creek near Fraser, Colo.

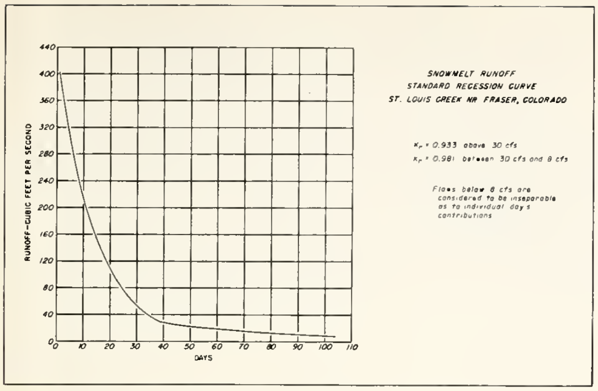


Figure 62. Snowmelt runoff recession curve for St. Louis Creek near Fraser, Colo.

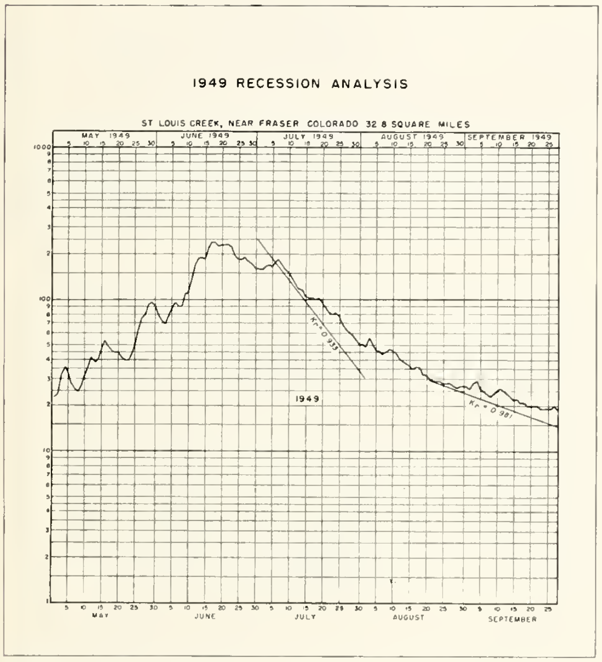


Figure 63. Application of recession slopes to a semilogarithmic plot of the 1949 hydrograph.

rived by this method of computation, for a drainage basin of only 32.8 square miles. On larger drainage basins where base flow alone might amount to sizable volumes of daily flow, it may not only be practical, but also necessary, to segregate day's contributions to ground-water flow.

C. Segregation of base flows by recession analyses

In the computation of daily contributions to the streamflow of St. Louis Creek, as used throughout this investigation, a constant base flow of 8 c. f. s. was assumed, below which recessions were not applied, and recession coefficients of 0.933 for flow above 30 c. f. s. and 0.981 for flows between 30 and 8 c. f. s. were used. The possible ground-water influence on the application of the recession concept was also investigated by use of the Barnes [8] concept as follows: Hydrographs for the years 1943–44, 1944–45, 1947–48, 1948–49, 1949–50 and 1950 to July 1951, were plotted by Bertle [14] on semilogarithmic paper in the manner illustrated by figure 63.

The slope of the recession coefficient of 0.981 for flows below 30 c. f. s. appeared to fit the falling stages through the winter when the hydrograph rose and fell periodically. However, it was reasoned that these wintertime fluctuations were possibly synthetic, due to the effect of ice and inaccuracies in the measurement system at low flows; and that it would be more reasonable to smooth out these fluctuations to get an average ground-water recession rate. The slopes of the ground-water recession rate were found to be:

December 11, 1943 to April 3, 1944: K=0.99825
December 1, 1944 to March 19, 1945: K=0.99742
January 10, 1948 to April 15, 1948: K=0.99827
December 1, 1948 to April 14, 1949: K=0.99870
December 5, 1949 to April 3, 1950: K=0.99742

The average base flow recession rate, as computed from these 5 years of winter flow, was: K=0.99801.

The average base flow recession curve, using a wintertime rate for K=0.998 was plotted for each winter's flow back under the snowmelt hydrograph of the preceding season for the years 1944, 1948, 1949, and 1950. These base flows were subtracted from the observed flows and the net hydrographs were plotted. As shown in figure 66, the falling portions of these net hydrographs showed a constant recession rate of 0.933. Figure 66 shows the distribution of points obtained when the net discharge of the daily average flow is plotted on the "y" axis against the daily average net discharge of the preceding day. The points on figure 66 show very little scatter about the line having a slope: K=0.933.

The next factor to be considered was that of the transition of the ground-water discharge rate during the spring runoff period. One assumption was that the ground-water discharge rate would increase logarithmically from the start of the hydrograph rise to a point just under the peak. The rates of these ground-water rises were found to be:

April 7 to June 21, 1943: K=1.0037
April 3 to June 3, 1948: K=1.0096
April 3 to June 17, 1949: K=1.0085
April 14 to June 17, 1949: K=1.0099
April 3 to June 17, 1950: K=1.0051

The average base flow increase rate, as computed from the above 4 years was found to be: K=1.0069.

A comparison was then made of the volume of flow computed through the use of recession coefficients of 0.933 and 0.981, without base flow other than a constant flow of 8 c. f. s. and the volumes recognizing base flow. The base flow volumes were computed as follows:

(a) The ground-water recession from the winter of 1948–49 was drawn with a slope of K=0.998 and extended back under the 1948 hydrograph to a point where it intersected the rising limb of the hydrograph, April 27.

(b) The most rapid possible increase in ground-water flow for the 1947–48 winter recession to the above-mentioned extension of the 0.998 recession was then drawn.

(c) A ground-water increase from the 1947–48 recession, on April 15, to the 1948–49 recession just under the peak day, June 3, was drawn.

(d) The ground-water increase using the average rate of K=1.0069, as determined above, was then drawn.

This resulted in various combinations of ground-water curves which could be chosen for this analysis. For example, the curve of (a) could be used in conjunction with either the curve of (b), (c), or (d). This comparison was based on the data for the period May 14 through June 5, 1948, 23 days. The results of this comparison are summarized in table 11.

Two of the equations, using curves (d) and (a) are illustrated in figure 67. On all of the plottings of the five equations, the points closely approximate a 45-degree line, and the correlation coefficient for four out of the five equations is about 0.91. From these correlations, it was concluded that there will be no significant difference in application of the volumes as computed by the two basic approaches to the use of recession coefficients.

On the basis of the study for the 1948 season, it was concluded that the recession method, using a K_r of 0.933 for flows above 30 c. f. s. and K_r of 0.981 for flows between 30 and 8 c. f. s., and neglecting the flow below 8 c. f. s., give results not significantly different from those attained through the inclusion of base flow increases in individual day's contribution computations, either when the base flow is included as an increase or volumes are computed above the base flow. Since

Table 11—Comparison between volumes of a day's contribution to snowmelt runoff computed with and without base flows

Period: May 14 through June 5, 1948 (23 days)

Y=the volume in c. f. s. days of 1 day's contribution to the snowmelt hydrograph, using base flows as computed through the use of the base flow curves designated in the left-hand column.

X=the volume in c. f. s. days of 1 day's contribution to the snowmelt hydrograph as computed, using K_r=0.933 for flows above 30 c. f. s. and K_r=0.981 for flows between 30 and 8 c. f. s.

Base flow curves used	Equation	Standard deviation s	Coefficient of simple correlation r
	Volume above base flow		
(b)+(a)	Y=0.985X−2.67	42. 71	0. 910
(c)+(a)	Y=0.984X−2.92	42. 67	0. 910
(d)+(a)	Y=0.985X−1.44	42. 87	0. 910
	Volume including the base flow increase		
(c)+(a)	Y=1.031X+54.14	50. 71	0. 888
(d)+(a)	Y=0.984X+50.41	42. 94	0. 909

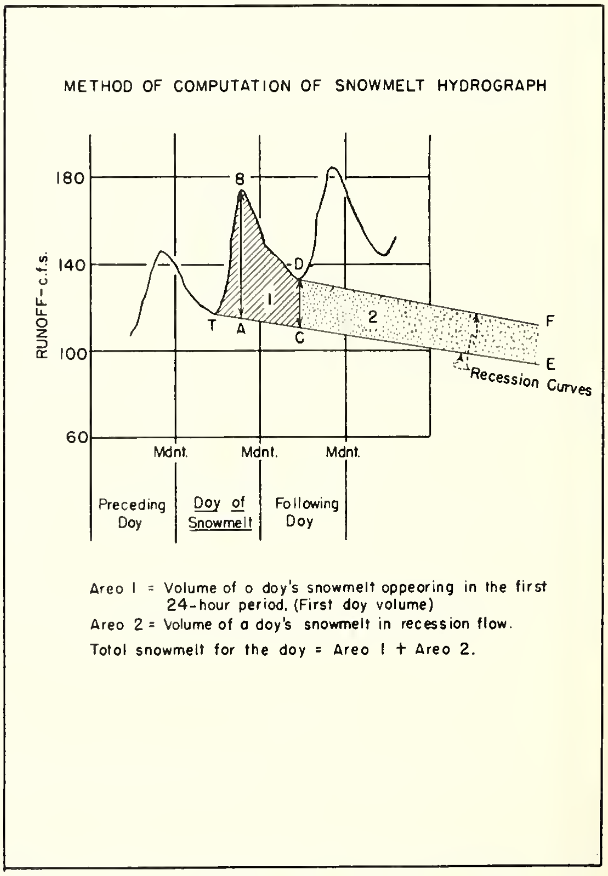


Figure 64. Separation of snowmelt hydrograph showing contribution from one day's melt.

the method using coefficients of $K_r=0.933$ and 0.981 requires much less work in the computation of daily volumes, and since it does not require a forecast of the level of the ground-water recession curve which is, in our present state of knowledge, at best an assumption, it was concluded that the use of the two coefficients, disregarding the volumes below 8 c. f. s. and without inclusion of base flow, was adequate for the snowmelt correlation analyses of the St. Louis Creek Drainage Basin having an area of 32.8 square miles which is the subject of this investigation.

In dealing with larger drainage basins having characteristics differing from those of St. Louis Creek and especially in dealing with drainage basins in which rainfall at different times of the year might have an important influence upon the base flow, the technique described above of recognizing base flow as an important factor in the hydrograph would most likely need to be applied.

D. Determining volume of one day's contribution

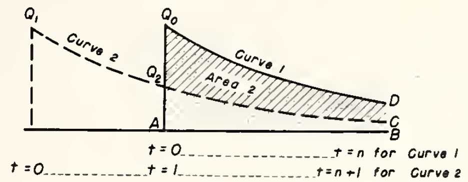
The volumes comprising a given day's contribution to the snowmelt hydrograph are delineated in figure 64. In figure 64, Point T, preceding trough of a day's hydrograph, is the point of inflection at which the hydrograph begins to rise under the effect of the contributions of the melt during the day. Point B is the peak of the day's snowmelt runoff. Point D is the trough of the day's runoff which peaks at Point B. The line from T to E is the recession line, using the coefficient (in this case, 0.933, since the runoff is above 30 c. f. s.) of the preceding day's snowmelt. The area TBDC, identified as Area 1, is the volume of the day's contribution appearing in the first 24-hour period, hereafter referred to as the first day's volume. The line DF is a recession curve having a coefficient of 0.933 as applied to Point D, which is the trough of the day's snowmelt. The area CDFE, identified as Area 2, expresses the volume between the two recession curves which resulted from the day's contribution of snowmelt not appearing as runoff on that day but which continues to contribute to the makeup of the snowmelt hydrograph. The total day's contribution to the snowmelt hydrograph is the sum of Areas 1 and 2.

Area 1, the first day's volume, has been determined in this series of investigations by planimeter, and its shape is a reflection of the rate of heat increase and decline during the day rather

RECESSION OF HYDROGRAPH

$$Q = Q_0 K_r^t$$

$$R = \int Q\,dt = \int Q_0 K_r^t\,dt = Q_0 \frac{K_r^t}{\log_e K_r}\Big|_0^t$$



Area Q_0ABD: $\quad Q_0 \frac{K_r^t}{\log_e K_r}\Big|_0^n = Q_0\left[\frac{K_r^n}{\log_e K_r} - \frac{K_r^0}{\log_e K_r}\right] = Q_0\left[\frac{K_r^n - 1}{\log_e K_r}\right]$

Area Q_2ABC: $\quad Q_1 \frac{K_r^t}{\log_e K_r}\Big|_1^{n+1} = Q_1\left[\frac{K_r^{n+1}}{\log_e K_r} - \frac{K_r^1}{\log_e K_r}\right] = K_rQ_1\left[\frac{K_r^n - 1}{\log_e K_r}\right]$

Difference: Area 2 $= Q_0\left[\frac{K_r^n - 1}{\log_e K_r}\right] - K_rQ_1\left[\frac{K_r^n - 1}{\log_e K_r}\right] =$

$$\frac{Q_0(K_r^n - 1) - K_rQ_1(K_r^n - 1)}{\log_e K_r} \quad \text{or} \quad \frac{(Q_0 - K_rQ_1)(K_r^n - 1)}{\log_e K_r}$$

$\log_e K_r = 2.30259 \log_{10} K_r$. $\quad Q$ = Flow in cfs at time t.

t = time in days. $\quad K_r$ = Runoff recession constant.

Q_0 = Flow in cfs at time $t=0$. $\quad R$ = Area under recession curve in cfs days.

Figure 65. Computation of recession volume.

than a drainage basin characteristic, as can be ascertained from an inspection of hundreds of individual day's rises. The recession contribution, Area 2, was determined through the application of calculus as shown on figure 65 and described below.

Barnes [8] expressed a single valued recession above a horizontal base line in an exponential equation:

$$Q = Q_0 K_r^t$$

in which:

- Q is the flow in c. f.s at time, t
- Q_0 is the flow in c. f.s at the beginning of the computation period or when time, t, equals 0 days
- t is the time in days
- K_r is the daily runoff recession coefficient.

The application of this equation to the two recession curves discussed in figure 64 led to the development of a method, illustrated in figure 65, of computing the recession contribution to the hydrograph by a procedure of integral calculus.

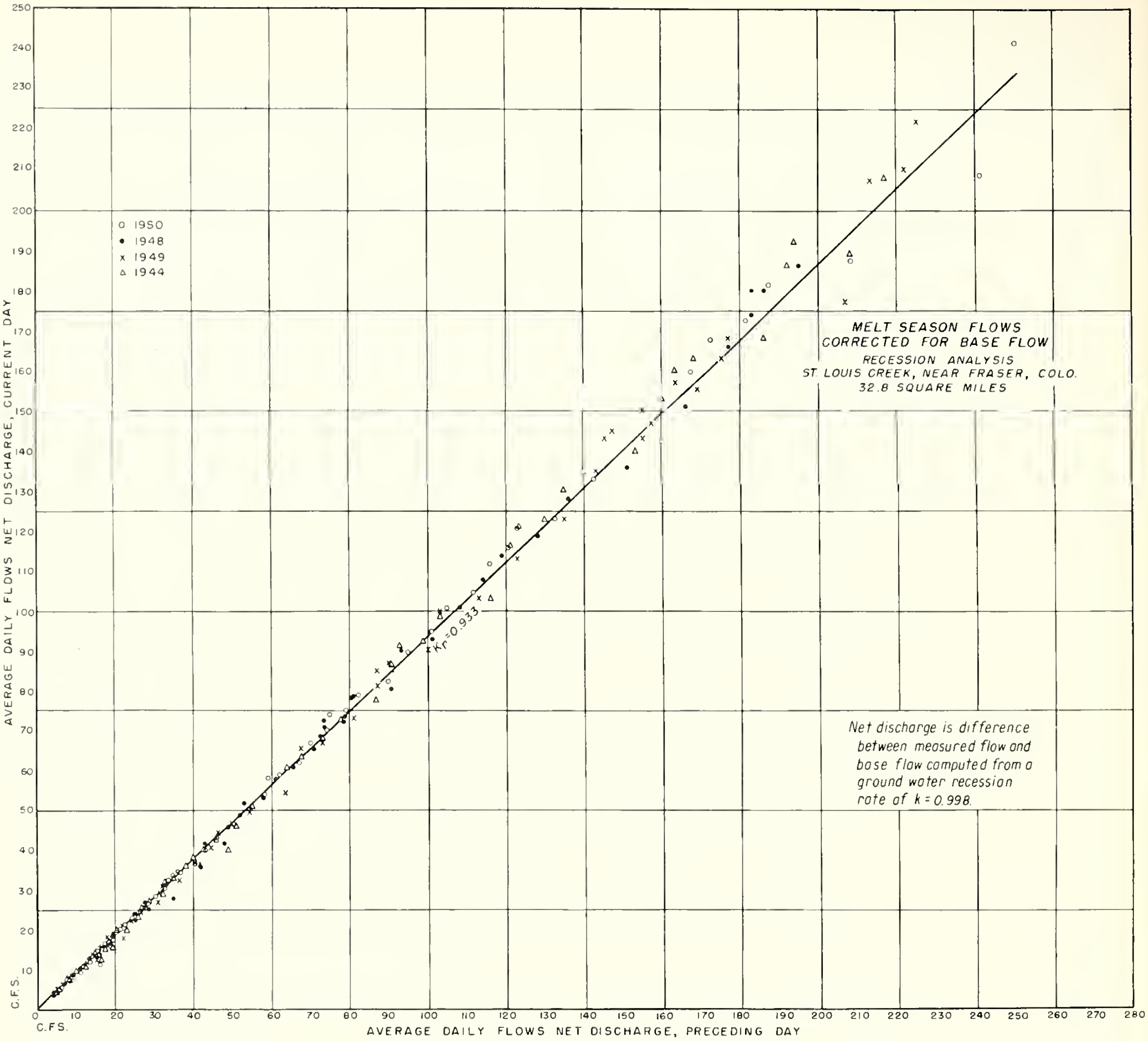


Figure 66. Recession analysis using net flows above base flow.

Moody [73] has expressed the equation for a recession line in another form as follows:

$$Q = Q_0 e^{-kt}$$

Moody's k is related to Barnes' K_r as follows:

$$k = -\log_e K_r$$

In Moody's restatement of the recession equation, k has the dimension: (time) to the minus 1 power. Moody's equation might offer advantages in computational procedures, depending upon the type of data-processing machinery available for use in making snowmelt runoff computations. Both equations yield identical results.

The results of the application of the recession concept to a day's contribution to the snowmelt hydrograph of St. Louis Creek are to be presented in a subsequent chapter of this report. In summary, it was found that, on the average, for the 1948 snowmelt season, 11.2 percent of a day's contribution to the runoff, Areas 1 plus 2 of figure 64, appeared on the first day as Area 1; for the 1949 snowmelt season, 11.7; and for the 1950 season, 13.2 percent. The remaining portion of a day's contribution—88.8, 88.3, and 86.8 percent, respectively, for the 3 years above mentioned—constitute the recession flows. It was found that the daily peak of snowmelt occurred about 8 to 10 p. m. on the day of the snowmelt, and the

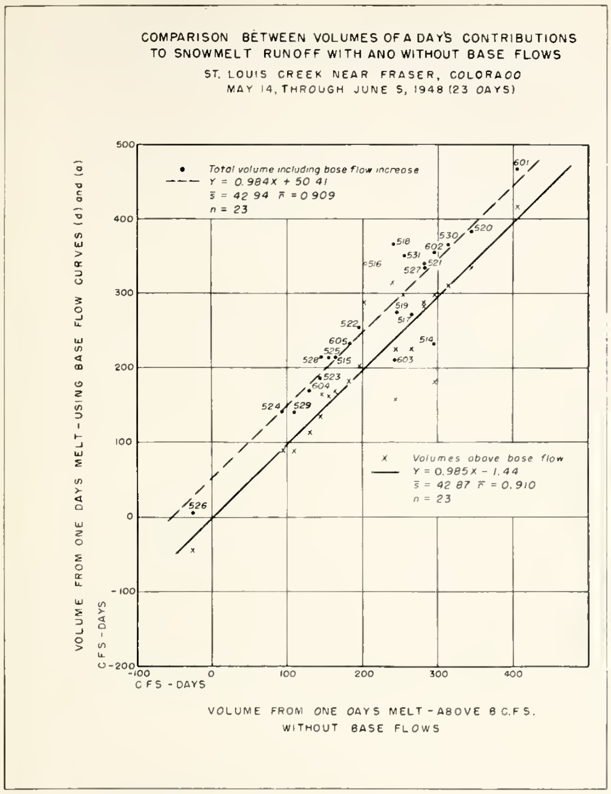


Figure 67. Comparison between volume of a day's contributions to snowmelt runoff with and without base flows.

trough of the day's melt occurred at about noon of the following day. The time of occurrence of the peaks and troughs was contingent to a considerable extent upon the distribution of melt conditions and varied widely at the exact hour of occurrence.

In order to determine the time lag, or length of time that elapses between the presence of melt conditions and the appearance of that melt as runoff measured in a stream, the plotting of hourly temperatures recorded by the hygrothermograph at the Fraser Headquarters Station was compared with an hourly plotting of flow in c. f. s. at St. Louis Creek gaging station, drainage area of 32.8 square miles. There seems to be approximately a 6-hour displacement between the peaks of the temperature curve and the peaks of the runoff curve. The time lag would then be 6 hours plus a multiple of 24 hours, but observations of men working in the Forest indicated that the lag was about 6 hours. This determination of the time lag was further substantiated by the fact that the time lag of Fool Creek, one of the tributaries of St. Louis Creek, was only 3 hours. When comparing the difference in drainage areas and the distance from the Fool Creek to the gaging station on St. Louis Creek, it seemed logical that the lag time for the larger area should be 6 hours rather than 30 hours. Accordingly, analyses correlating factors causing snowmelt with streamflow, as used throughout this investigation, applied the time lag of 6 hours to the St. Louis Creek investigation and 3 hours to the Fool Creek investigation.

At times, the trough of a day's contribution to snowmelt runoff fell below the recession line of the preceding day, resulting in negative volume of contribution. In a few instances, the negative volume was almost equal, numerically, to the first day's contribution, so that the total day's contribution, as secured by algebraic summation of the two volumes, amounted to either a very small number of acre-feet or actually a negative total. The volumes computed with a negative sign for a day's contribution were used with the sign unchanged in correlation analyses. Negative volumes were observed not only at St. Louis Creek but also in drainage basins as large as the South Fork of the Flathead River above Hungry Horse Dam, having a drainage area of 1,640 square miles.

A frequent recurrence of negative volume might be interpreted to mean that the recession coefficient being used was not truly representative of purely snowmelt contributions to runoff. However, field observations and the results of the analyses indicated that negative volumes could result from sudden and short-duration freezing of melt waters in transit in subsurface water courses or in small channels. Such a sudden freeze would, in effect, subtract from the hydrograph certain portions of a day's total contribution to runoff and produce a retrogression of the hydrograph, causing the trough to fall below the recession line of some preceding day's contribution. Such temporarily impounded subsurface flows, which were abstracted from the hydrograph, would become available upon subsequent thawing and would appear and be credited to a subsequent day's snowmelt. Although this tended to weaken the correlations secured by short-period studies, it supports the decision to use negative volumes in correlation analyses, since the runoff had been yielded by the snowmelt and

returned to the channel following its release from the temporary impoundment by freezing. The above discussion offers possible explanations for the appearance of negative volumes. However, an exact explanation would require further investigation, justifiable only if it were pertinent to a specific application of snowmelt runoff computations.

SECTION 8—ANALYSIS OF THE SNOWMELT HYDROGRAPH

Hourly discharges in cubic feet per second for the St. Louis Creek drainage basin 32.8 square miles, and for Fool Creek, an area of 1.11 square miles, are given in appendix B, "Basic Data."

Figures 68, 69, and 70 show, respectively, for the 1948, 1949, and 1950 snowmelt seasons the snowmelt runoff hydrographs and related meteorological factors as follows:

a. Solar radiation upon a horizontal surface as measured at Shadow Mountain station near Grand Lake, Colo. Hourly values in gram calories per square centimeter for the hour ending are plotted on the graph, and the total gram calories per square centimeter incident for the day is given for each day.

b. Wind at the 47.4-foot level above the ground from the windtower anemometer in the open at West St. Louis Creek. A graph is given of the wind in miles for the hour ending, and the total number of miles of wind for the day is given for each day.

c. Dewpoint temperature at the headquarters station. Hourly values of dewpoint computed from hydrothermograph records are plotted in the graphical form. The average dewpoint temperature for the day is entered for each day.

d. Air temperature at the headquarters station in degrees Fahrenheit. Hourly values of air temperature are plotted on the graph and degree-days above 32° computed from the thermograph trace are given for each day.

e. Runoff, as recorded, is plotted in hourly values on a hydrograph for the St. Louis Creek gaging station near Fraser, Colo. The recession lines, as computed by the method outlined in the preceding chapter, have been entered on the hydrographs, and the total contribution to the runoff from the day's snowmelt is given in acre-feet, as computed by the recession method previously discussed.

The following characteristics of individual day's contributions to the snowmelt hydrograph were measured and are given in tables 12, 13, and 14, which are, respectively, for the 1948, 1949, and 1950 snowmelt seasons: Height to trough, height to peak, first day's volume—Area 1 of figure 64; recession contribution of the day's snowmelt—Area 2 of figure 64; and the total day's contribution to the snowmelt runoff—the sum of Areas 1 and 2 of figure 64.

Figure 71 is a double mass curve of the volume of the first day's contribution in relation to the total runoff contribution from a day's melt for the snowmelt seasons 1948, 1949, and 1950. A distinct elbow develops in the double mass curve either the very day or in proximity to the day of the peak volume contribution to the snowmelt hydrographs. This is the day for the snowmelt season for which the sum of the first day's and the recession contributions to the total hydrograph is the greatest and is not necessarily the day of the

Table 12—Runoff volumes, St. Louis Creek, 1948

Date	Trough [1] (c. f. s.)	Peak [2] (c. f. s.)	Net first day volume above recession [3] (acre-feet)	Volume of recession contribution [4] (acre-feet)	Total of the day's contribution [5] (acre-feet)
May 13	15	31	29	729	758
14	25	52	34	554	588
15	36	66	37	288	325
16	46	80	42	362	404
17	58	105	60	469	529
18	72	102	35	444	479
19	86	126	52	435	487
20	96	155	67	619	686
21	113	165	64	495	559
22	124	180	63	329	392
23	128	168	46	238	284
24	128	142	19	167	186
25	126	168	42	270	312
26	128	128	4	−55	−51
27	117	155	47	512	559
28	128	165	44	248	292
29	128	140	16	202	218
30	128	172	64	563	627
31	140	180	63	445	508
June 1	148	191	65	743	808
2	165	239	88	505	593
3	172	242	85	397	482
4	175	233	64	195	259
5	170	230	64	297	361
6	170				

[1] Trough is Point T of figure 64.
[2] Peak is Point B of figure 64.
[3] Net first day volume is Area 1 of figure 64.
[4] Recession volume is Area 2 of figure 64.
[5] Total runoff volume is Area 1 plus Area 2.

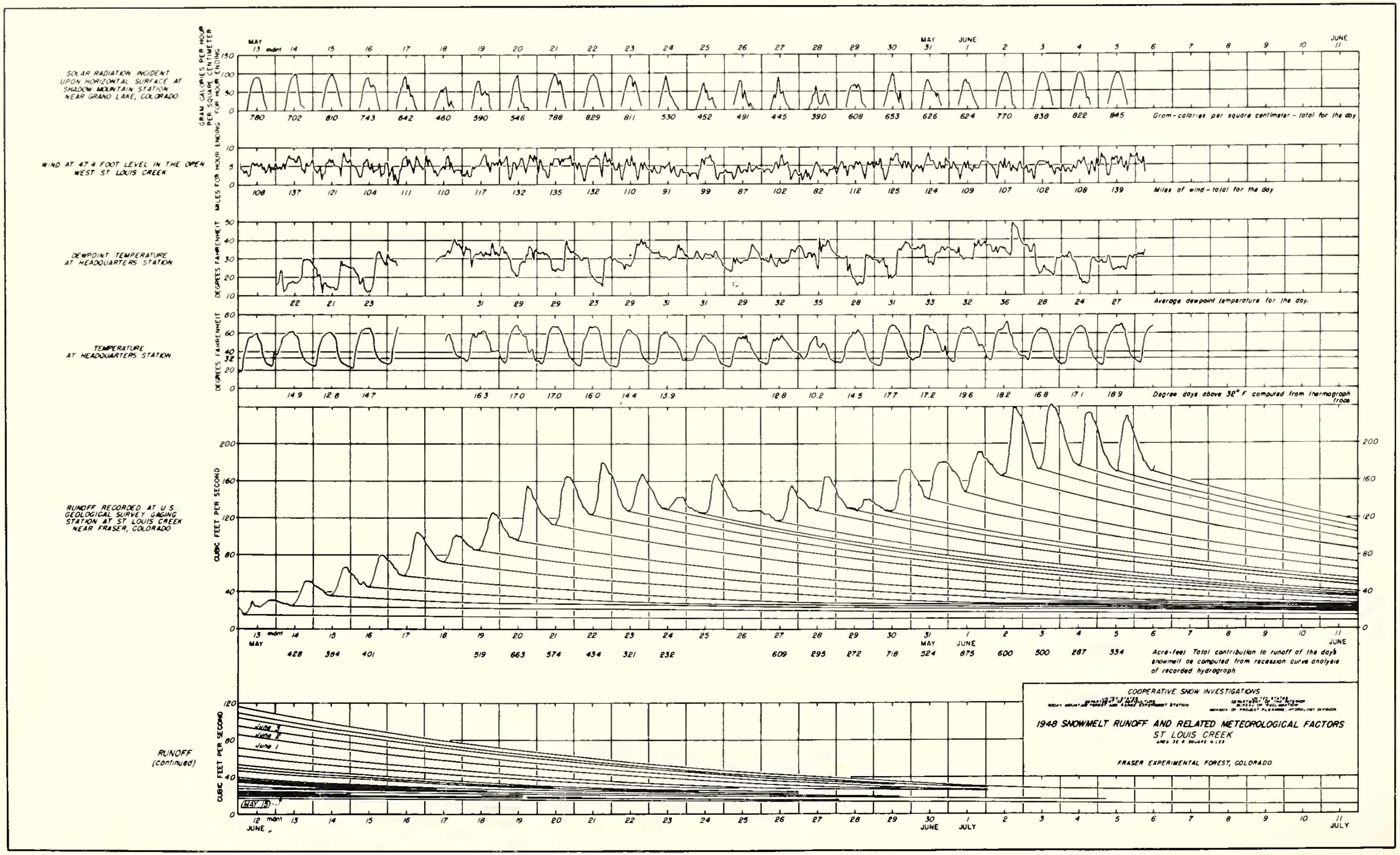


Figure 68. Snowmelt runoff and related meteorological factors, St. Louis Creek, 1948.

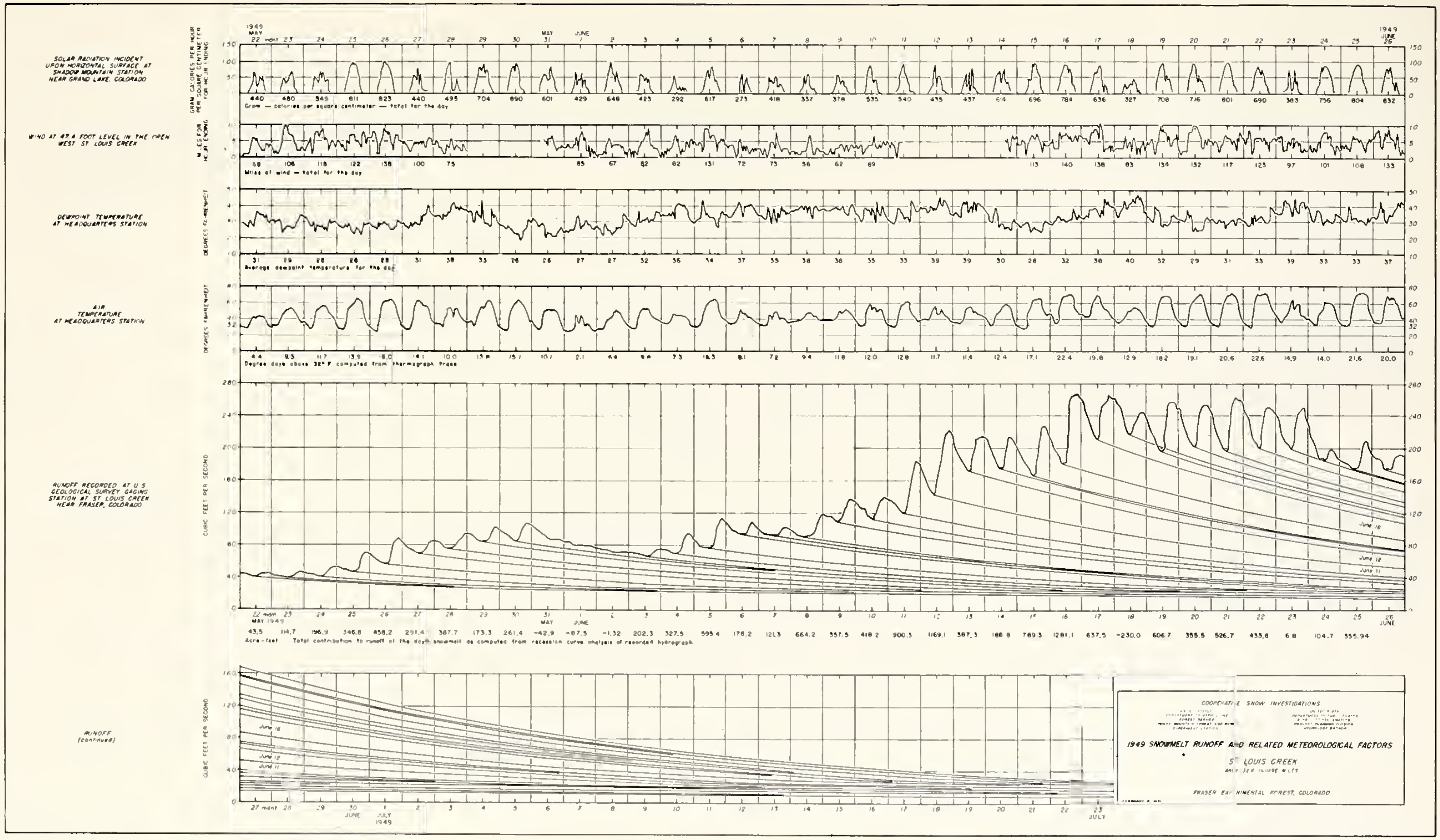


Figure 69. Snowmelt runoff and related meteorological factors, St. Louis Creek, 1949.

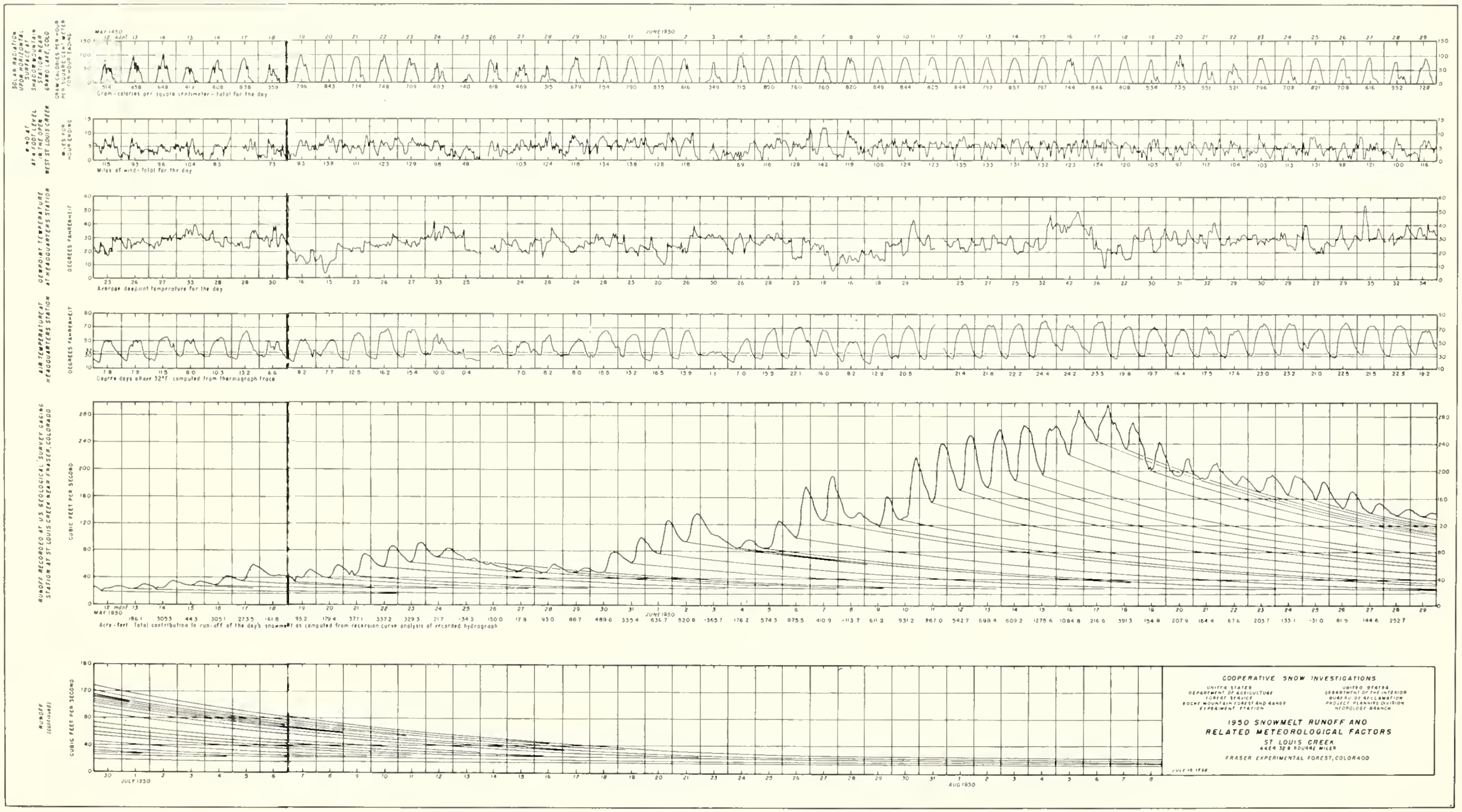


Figure 70. Snowmelt runoff and related meteorological factors, St. Louis Creek, 1950.

maximum rate of discharge of the runoff. The days of peak contribution to the hydrograph were: June 1, 1948, June 16, 1949, and June 15, 1950.

The appearance of the elbow in the double mass curve of figure 71 is not surprising in the light of the relationship disclosed between the volume of water equivalent remaining in the drainage basin, the area covered by the snow pack, and the time for occurrence of the peak runoff as discussed in section 6, "Snow Disappearance." The significance of this change in the relationship between the first day's volume and the total day's contribution to the snowmelt runoff will be considered in greater detail in section 11, on synthesizing the snowmelt hydrograph.

Table 13—Runoff volumes, St. Louis Creek, 1949

Date	Trough [1] (c. f. s.)	Peak [2] (c. f. s.)	Net first day volume above recession [3] (acre-feet)	Volume of recesssion contribution [4] (acre-feet)	Total of the day's contribution [5] (acre-feet)
May 19	45	51	10	94	104
20	46	46	0	2	2
21	43	45	2	−2	0
22	40	44	5	39	44
23	39	45	10	105	115
24	41	52	17	180	197
25	46	70	31	316	347
26	56	87	40	418	458
27	69	84	22	269	291
28	75	94	27	361	388
29	84	102	22	151	173
30	84	107	32	229	261
31	87	87	−1	−42	−43
June 1	80	80	0	−67	−67
2	72	74	3	−4	−1
3	67	75	14	188	202
4	70	94	30	297	327
5	77	113	47	548	595
6	93	109	16	162	178
7	93	102	11	110	121
8	91	118	36	628	664
9	109	138	42	315	357
10	113	140	39	379	418
11	120	184	80	820	900
12	142	223	109	1, 060	1, 169
13	172	214	61	326	387
14	172	214	49	138	187
15	166	226	77	712	789
16	181	265	126	1, 155	1, 281
17	211	265	83	554	637
18	217	244	30	−260	−230
19	193	256	87	520	607
20	199	253	72	284	356
21	196	262	84	443	527
22	199	250	68	366	434
23	199	250	52	−45	7
24	184	196	14	91	105
25	175	208	36	320	356
26	175	------	--------	--------	--------

[1] Trough is Point T of figure 64.
[2] Peak is Point B of figure 64.
[3] Net first day volume is Area 1 of figure 64.
[4] Recession volume is Area 2 of figure 64.
[5] Total runoff volume is Area 1 plus Area 2.

The dissimilarity in the relationships of the various components of the day's contribution to the total runoff is further illustrated in figures 72 and 73. The relation between the first day's volume (Area 1 of figure 64) and total runoff (Areas 1+2 of figure 64) for the 1948–49 snowmelt seasons for St. Louis Creek is shown in figure 72 computed for a total of 62 days, including those before and after the peak, and separately for 49 days through the day of peak volume con-

Table 14—Runoff volumes, St. Louis Creek, 1950

Date	Trough [1] (c. f. s.)	Peak [2] (c. f. s.)	Net first day volume above recession [3] (acre-feet)	Volume of recession contribution [4] (acre-feet)	Total of the day's contribution [5] (acre-feet)
May 13	22	30	9	177	186
14	24	35	12	293	305
15	28	35	7	37	44
16	28	42	18	287	305
17	34	59	34	239	273
18	42	44	−2	−60	−62
19	37	51	15	80	95
20	38	58	23	156	179
21	42	74	42	335	377
22	54	87	42	295	337
23	62	92	37	292	329
24	70	86	18	4	22
25	65	68	1	−35	−35
26	59	55	−8	−142	−150
27	49	55	5	13	18
28	47	61	16	77	93
29	47	54	10	77	87
30	47	79	44	446	490
31	62	102	50	485	535
June 1	77	126	62	575	637
2	94	135	56	465	521
3	105	96	−15	−351	−366
4	86	96	16	160	176
5	86	126	54	560	574
6	100	172	93	883	976
7	126	191	67	344	411
8	131	138	5	−119	−114
9	117	162	48	563	611
10	131	218	104	827	931
11	152	239	114	753	867
12	170	251	96	447	543
13	175	260	105	593	698
14	185	266	106	503	609
15	191	263	113	1, 163	1, 276
16	221	284	97	988	1, 085
17	242	296	64	153	217
18	230	269	27	−418	−391
19	200	239	34	121	155
20	191	215	22	186	208
21	185	209	30	134	164
22	178	191	16	52	68
23	168	191	35	169	204
24	162	191	41	92	133
25	155	182	26	−57	−31
26	142	168	27	55	82
27	135	150	20	125	145
28	131	142	18	235	253
29	131				

[1] Trough is Point T of figure 64.
[2] Peak is Point B of figure 64.
[3] Net first day volume is Area 1 of figure 64.
[4] Recession volume is Area 2 of figure 64.
[5] Total runoff volume is Area 1 plus Area 2.

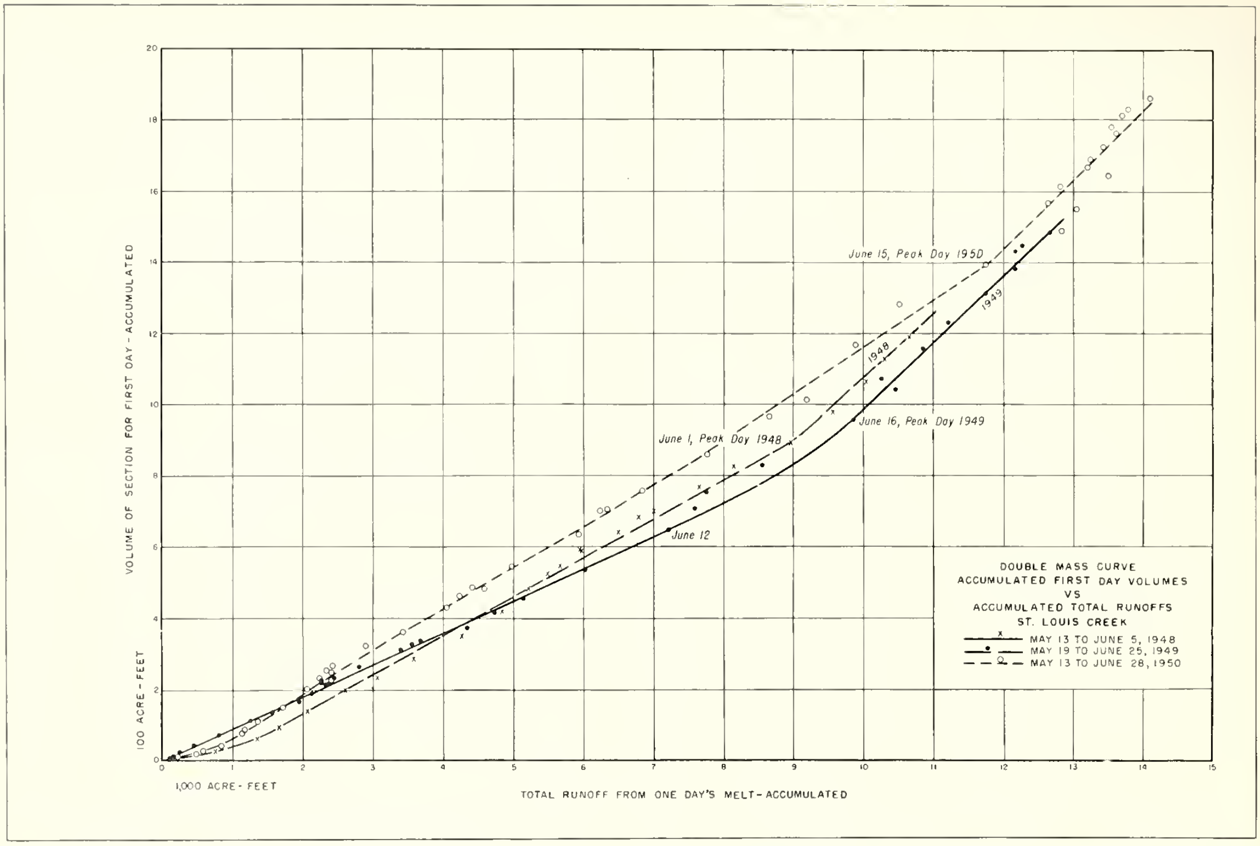


Figure 71. Double mass curves for 1948, 1949, and 1950 of accumulated first-day volumes vs. accumulated total runoffs in St. Louis Creek.

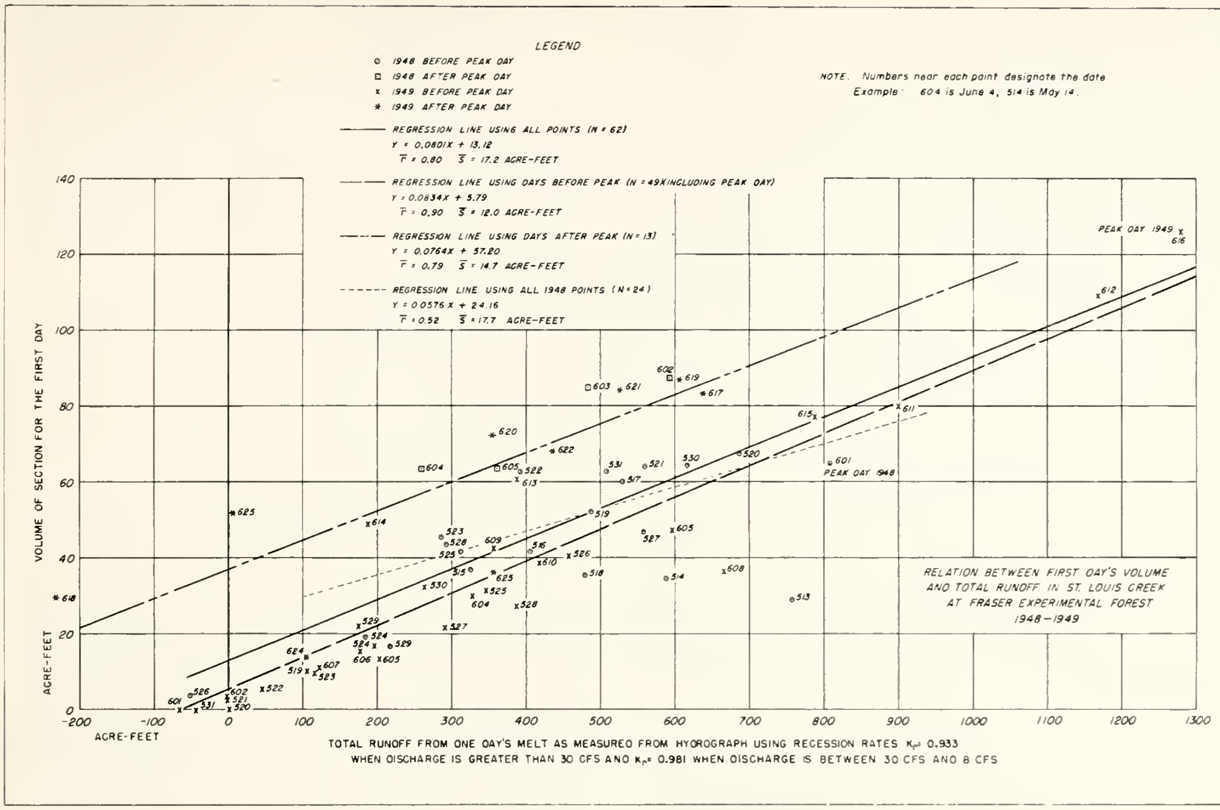


Figure 72. Relation between first day's volume and total runoff from one day's melt

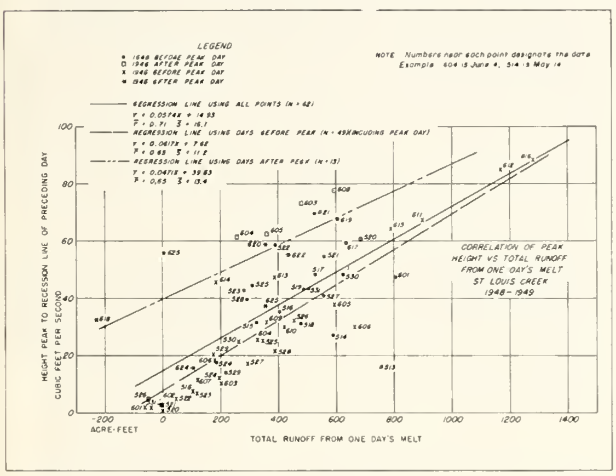


Figure 73. Relation between height to peak and total runoff from one day's melt.

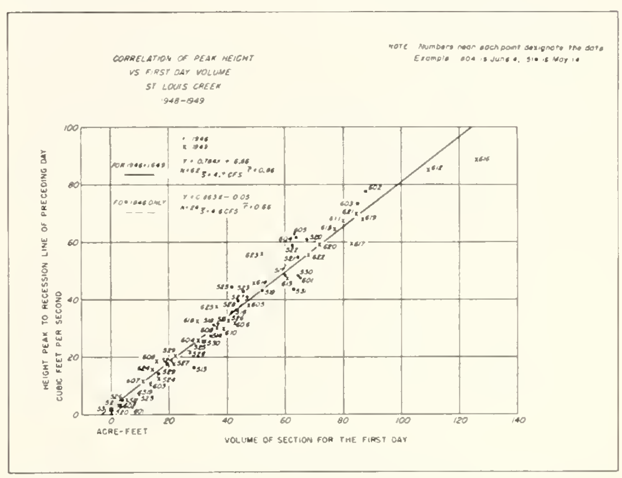


Figure 74. Relation between height to peak and first day's volume for 1948 and 1949.

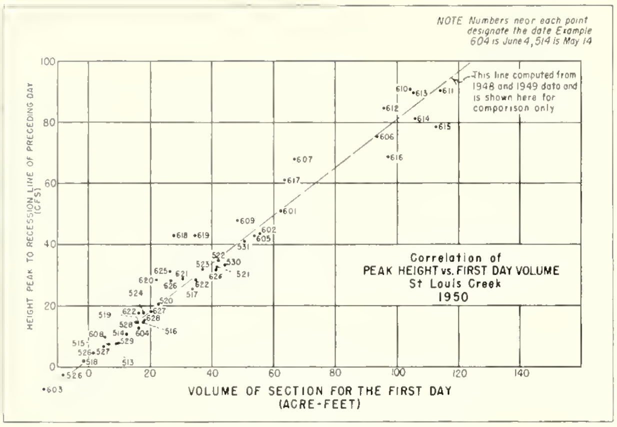


Figure 75. Relation between height to peak and first day's volume for 1950.

tribution, and for the 13 days after the peak day of volume contribution.

The relationship between the height to the peak above the recession line of the preceding day (line BA of figure 64) versus the total contribution of

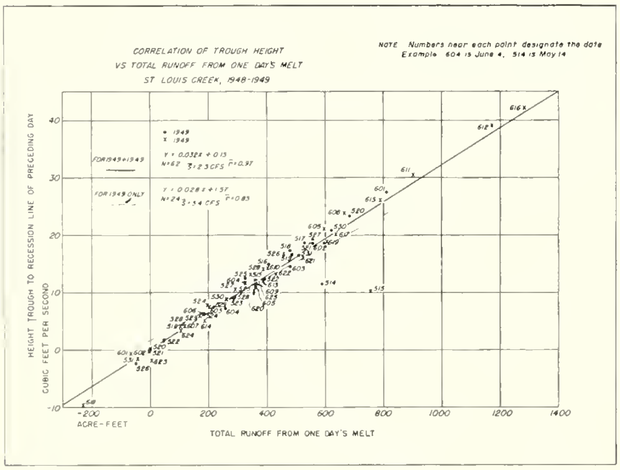


Figure 76. Relation between height to trough and total runoff from one day's melt for 1948 and 1949.

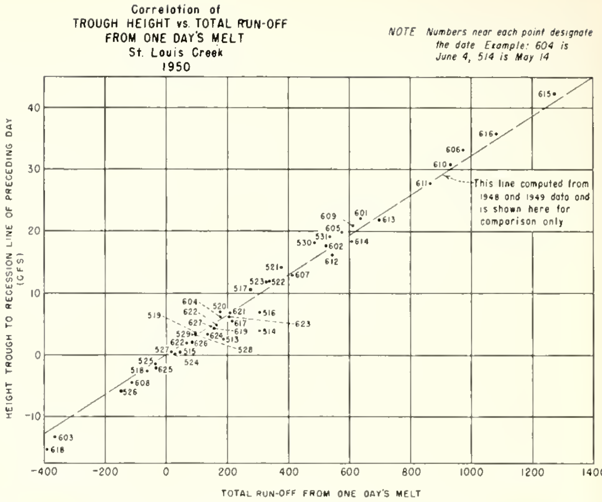


Figure 77. Relation between height to trough and total runoff from one day's melt for 1950.

a day's snowmelt is shown in figure 73. Again, there is a big difference in the positioning of the regression line for the 49 points, including the days of peak contribution, for the 62 points, considering all days, and for 13 points, including only those days after the day of peak contribution.

The relationship between the height to peak above the recession line of the preceding day and the volume of the first day's contribution is shown in figure 74 for 1948 and 1949. The coefficient of simple correlation, r, for the points for 1948 and 1949 combined, a total of 62 points, is r=0.98. The relationship of this line to the values for 1950 is shown in figure 75. It is obvious that the 1950 data are in accord with the relationship computed for 1948 and 1949.

Figure 76 shows the relationship between the height of the trough above the recession line of the preceding day's contribution versus the total runoff from a day's contribution to the snowmelt hydrograph. Figure 77 shows the regression line

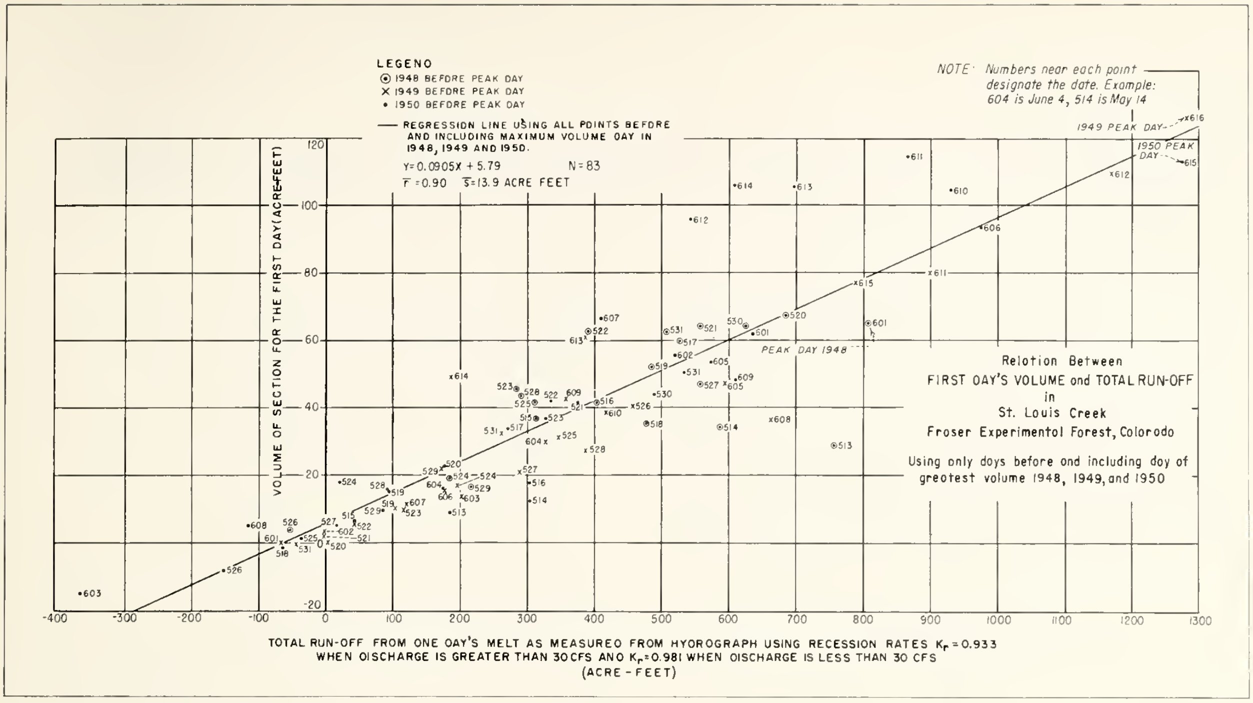


Figure 78. Relation between first day's volume and total runoff from one day's melt using only days before and including day of greatest volume.

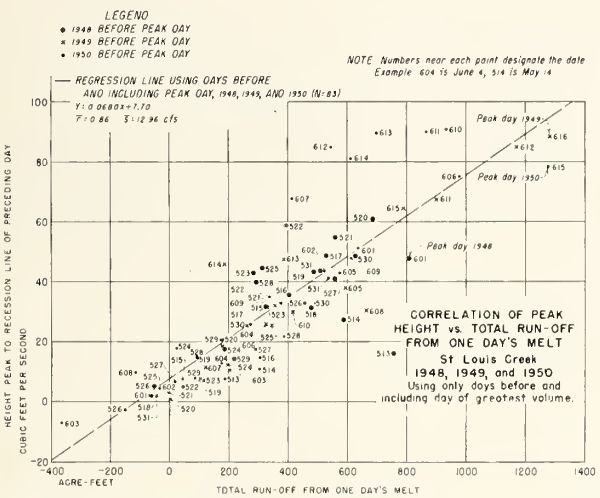


Figure 79. Relation between height to peak and total runoff from one day's melt using only days before and including day of greatest volume.

of figure 76, around which has been added the points for the 1950 snowmelt season. Again, the relation between these two characteristics of a day's contribution to the snowmelt hydrograph is very strong.

The relation between the first day's volume and the total runoff from a day's contribution to the snowmelt hydrograph for a total of 83 days from the 1948, 1949, and 1950 snowmelt seasons for the rising portion of the hydrograph, including the day of greatest volume contribution, was found to be r=0.90, as shown in figure 78. The relation between the height to peak and the total runoff from a day's contribution for the same 83 days, also using only those points on the rising hydrograph, including the day of the greatest volume, was found to have a correlation coefficient r=0.86 as is shown in figure 79.

SECTION 9—RELATING SNOWMELT RUNOFF TO ITS CAUSES

The factors affecting snowmelt and runoff from snowmelt can be analyzed through several approaches. Statistical correlation analyses can be computed relating snowmelt runoff to its causes. Also, the relationships can be expressed in equations derived from non-statistical considerations of the observed physical phenomena of nature.

A. The statistical approach

1. *Effect of recognizing the recession flows.* A study was made of the 1948 data to determine which hydrograph area of the three listed below would be correlated best with one of the major causative variables, degree-days above 32° F (X_2). The three hydrograph areas considered were:

X_0 equals total volume of runoff for 1 day as represented by the area under the hydrograph for 1 day and above a baseline of 0 flow bounded by vertical time lines at midnight.

X_1 equals total volume of runoff from 1 day's contribution as represented by the area under the hydrograph for 1 day, including the residual flow generated on that day but excluding the residual flow from snow previously melted. (Shown as Area 1 plus Area 2 in figure 64.)

X_{1A} equals the net volume of runoff for 1 day as represented by the area under the hydrograph for 1 day and above the recession of the preceding day (Area 1 of figure 64).

For the 1948 season, the adjusted correlation coefficient for the three simple correlation analyses were:

$\bar{r}=0.45$, for the equation $X_0=4.227X_2-3.85$

$\bar{r}=0.50$, for the equation $X_1=3.927X_2-1.66$

and

$\bar{r}=0.65$, for the equation $X_{1A}=5.436X_2-3.19$.

The above results show that the use of volumes computed by the recession principle offer a definite improvement over the use simply of the flow as measured for the day, as was expected, based upon the considerations discussed in detail in section 7. In view of the above results, it was not considered necessary to repeat similar correlation studies using data for the years subsequent to 1948.

2. *Correlation computations.* Both simple and multiple statistical correlation analyses were computed relating runoff to the various factors causing snowmelt. Correlation analyses were performed using the method outlined by Ford [37]. The factors used in this series of analyses are described in table 15. The independent variables

Table 15—List of variables used in statistical correlations

Identification	Description of variable	Units
X_1	Total runoff from 1 day's contribution to the hydrograph.	100 acre-feet.
X_{1A}	First day runoff volume above recession.	10 acre-feet.
X_2	Degree-days above 32° F at Headquarters.	10° days.
X_3	Degree-days above 50° F at Headquarters.	° days.
X_4	Daily total solar radiation at Shadow Mountain.	100 Ly.
X_5	Dew point temperature at Headquarters.	10° F.
X_6	Relative humidity at Headquarters.	10 percent.
X_7	Daily wind travel at 47.4 feet in open.	10 mile.
X_8	Daily wind travel at 1.4 feet in forest.	10 mile.
X_9	Daily wind travel at 24.9 feet in forest.	10 mile.
X_{10}	1000 to 1400 hour solar radiation at Shadow Mountain.	10 Ly.
X_{11}	Maximum temperature at Headquarters.	10° F.
X_{12}	Degree-days above 40° F at Headquarters.	° days.
X_{13}	Duration of temperature above 40° F at Headquarters.	10 hours.
X_{14}	Accumulated runoff April 1 to start of day plus recession in percentage of total runoff from April 1 to July 31.	10 percent.
X_{15}	Daily wind travel at 23.1 feet in open.	10 mile.
X_{16}	Daily wind travel at 1.4 feet in open.	10 mile.
X_{17}	Degree-days above 32° F at windtower.	10° days.
X_{18}	Degree-days above 40° F at windtower.	10° days.
X_{19}	Relative humidity at windtower.	10 percent.

considered were: Air temperature (daily maximum temperature or degree-days), duration of melting temperatures, relative humidity, dew point temperature, wind, solar radiation, and an index of the areal extent of the snow cover (accumulated runoff in percent of seasonal volume). These variables were combined in equations having one, two, three, four, and five independent variables as follows:

a. Temperature alone—Equations 32 and 33.

b. Temperature and wind—Equations 2 and 3.

c. Temperature and relative humidity—Equation 1.

d. Temperature, wind, and duration of temperature—Equations 12 and 13.

e. Temperature, wind, and dew point—Equation 5.

f. Temperature, wind, and relative humidity—Equations 6, 7, 8, 14, 15, 16, and 17.

g. Temperature, wind, and radiation—Equation 4.

h. Wind, relative humidity, and radiation—Equations 9, 10, and 11.

i. Temperature, wind, relative humidity, and duration of temperature—Equations 25 and 26.

j. Temperature, wind, relative humidity, and accumulated runoff—Equations 22 and 27.

k. Temperature, wind, relative humidity, and radiation—Equations 19, 20, 21, and 24.

l. Temperature, wind, dew point, and radiation—Equations 18 and 23.

m. Temperature, wind, relative humidity, duration of temperature, and accumulated runoff—Equations 28, 29, and 30.

Although several sources of data for temperature, wind, and ıelative humidity were available

Table 16—Summary of multiple

Equation No.	Dependent variable	Independent variables								
		X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
1	X1.26	4. 527				0. 387				
1A	X1A.26	6. 525				. 680				
2	X1.27	3. 452					0. 129			
2A	X1A. 27	5. 965					. 172			
3	X1.28	3. 753						0. 329		
3A	X1A.28	5. 508						−. 295		
4	X1.247	4. 569		−0. 628			. 292			
4A	X1A.247	5. 600		. 206			−. 226			
5	X1.257	2. 235			1. 731		. 426			
5A	X1A.257	5. 483			. 841		−. 050			
6	X1.267	4. 056				. 788	. 342			
6A	X1A.267	6. 498				. 704	. 020			
7	X1.268	5. 847				1. 608		1. 822		
7A	X1.A268	7. 171				1. 277		. 892		
8	X1.269	4. 926				1. 408			1. 528	
8A	X1A.269	6. 677				1. 069			. 582	
9	X1.467			−. 429		−. 109	. 510			
9A	X1A.467			. 710		. 902	. 279			
10	X1.67$\overline{10}$					. 242	. 511			−0. 023
10A	X1A.67$\overline{10}$					1. 016	. 255			. 158
11	X1.7$\overline{10}$ $\overline{19}$						. 546			−. 023
11A	X1A.7$\overline{10}$ $\overline{19}$						. 287			. 140
12	X1.7$\overline{11}$ $\overline{13}$						. 238			
12A	X1A.7$\overline{11}$ $\overline{13}$						−. 237			
13	X1.7$\overline{12}$ $\overline{13}$						. 316			
13A	X1A.7$\overline{12}$ $\overline{13}$						−. 229			
14	X1.7$\overline{17}$$\overline{19}$						. 333			
14A	X1A.7$\overline{17}$$\overline{19}$						. 003			
15	X1.$\overline{15}$ $\overline{17}$ $\overline{19}$									
15A	X1A.$\overline{15}$ $\overline{17}$ $\overline{19}$									
16	X1.$\overline{15}$ $\overline{18}$ $\overline{19}$									
16A	X1A.$\overline{15}$ $\overline{18}$ $\overline{19}$									
17	X1.$\overline{16}$ $\overline{17}$ $\overline{19}$									
17A	X1A.$\overline{16}$ $\overline{17}$ $\overline{19}$									
18	X1.2457	4. 093		−. 539	. 516		. 352			
18A	X1A.2457	3. 258		. 645	2. 296		. 038			
19	X1.2467	4. 622		−. 591		. 153	. 325			
19A	X1A.2467	6. 020		. 497		1. 239	. 037			
20	X1.2468	6. 468		−. 632		. 990		1. 879		
20A	X1A.2468	6. 696		. 484		1. 750		. 848		
21	X1,267 $\overline{10}$	4. 279				. 470	. 343			−0. 052
21A	X1A.267 $\overline{10}$	5. 992				1. 422	. 020			. 117
22	X1.267 $\overline{14}$	7. 192				1. 008	. 055			

from the instruments in operation in the Fraser Experimental Forest, in all of the correlation analyses, the data used were from only one station in any one series of analyses. The problem of attempting to combine data from more than one source was not approached in this series of investigations since, under practical operating conditions, the hydrologist feels fortunate if he finds even one source of data from within a drainage basin in which he is working. The integration of data from several sources, although it offers promise of improving correlations, would need to be thoroughly investigated as a separate study, since it would be complicated by exposure, aspect, and lapse rate considerations as well as the improbability that the data from all existing sources could be made available without delay to the practicing hydrologist when it is needed. Examples of the exposure and aspect effects on the meteorological factors are shown by the comparisons between the temperature and relative humidity recordings at Fool Creek and West St. Louis Creek stations. Figure 22 in section 4 illustrates the difference in air temperature at the two stations as indicated by the degree-days computed from the thermograph records. Figure 80 illustrates the difference in relative humidity at the two stations.

Table 16 presents the results of 64 equations for the 1948 snowmelt season; table 17 presents the results of 64 similar equations for the 1949 snowmelt season; and table 18 gives the statistical equations using the combined data for both the 1948 and 1949 snowmelt seasons. In this series of statistical analyses, the X_1 and X_{1A} have the same meaning as described earlier.

correlations using 1948 data

Independent variables—Continued									a	$\bar{R}$	Equation No.
X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}			
									−4. 84	0. 48	1
									−8. 84	. 66	1A
									−2. 40	. 47	2
									−6. 01	. 68	2A
									−2. 01	. 47	3
									−3. 87	. 62	3A
									−1. 74	. 63	4
									−2. 22	. 61	4A
									−8. 85	. 56	5
									−5. 10	. 63	5A
									−10. 34	. 50	6
									−9. 16	. 63	6A
									−17. 42	. 60	7
									−14. 99	. 66	7A
									−16. 13	. 61	8
									−13. 13	. 65	8A
									2. 22	. 25	9
									−7. 87	. 20	9A
									−2. 03	. 0	10
									−8. 82	. 25	10A
								0. 315	−2. 87	. 0	11
								. 964	−7. 75	. 25	11A
−0. 158		8. 785							−9. 83	. 67	12
3. 414		2. 447							−17. 86	. 62	12A
	−0. 158	9. 943							−11. 82	. 69	13
	. 634	. 292							1. 11	. 53	13A
						2. 735		. 530	−6. 49	. 48	14
						4. 921		. 475	−4. 86	. 72	14A
				0. 289		2. 837		. 468	−5. 48	. 46	15
				. 042		4. 887		. 520	−5. 47	. 72	15A
				. 295			3. 309	. 549	−4. 71	. 37	16
				−. 010			6. 528	. 693	−4. 41	. 72	16A
					. 660	3. 456		. 854	−9. 83	. 53	17
					. 132	4. 997		. 616	−6. 59	. 72	17A
									−3. 77	. 61	18
									−11. 18	. 69	18A
									−3. 35	. 60	19
									−15. 10	. 68	19A
									−10. 64	. 70	20
									−20. 16	. 70	20A
									−7. 27	. 47	21
									−16. 13	. 68	21A
			−. 490						−10. 67	. 64	22

Equation No.	Dependent variable	Independent variables X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
22A	X1A.267 $\overline{14}$	5.369				.628	.125			
23	X1.3457		.398	−.493	1.259		.478			
23A	X1A.3457		.418	.573	2.666		.102			
24	X1.3467		.604	−.818		−.049	.309			
24A	X1A.3467		.867	.149		.981	−.012			
25	X1.67 $\overline{11}$ $\overline{13}$					.762	.477			
25A	X1A.67 $\overline{11}$ $\overline{13}$					.377	−.118			
26	X1.67 $\overline{12}$ $\overline{13}$					.710	.489			
26A	X1A.67 $\overline{12}$ $\overline{13}$					.917	−.005			
27	X1.$\overline{14}$ $\overline{15}$ $\overline{18}$ $\overline{19}$									
27A	X1A.$\overline{14}$ $\overline{15}$ $\overline{18}$ $\overline{19}$									
28	X1.67 $\overline{11}$ $\overline{13}$ $\overline{14}$					.782	.246			
28A	X1A.67 $\overline{11}$ $\overline{13}$ $\overline{14}$					.363	.049			
29	X1.67 $\overline{12}$ $\overline{13}$ $\overline{14}$					.942	.247			
29A	X1A.67 $\overline{12}$ $\overline{13}$ $\overline{14}$					.782	.136			
30	X1.$\overline{11}$ $\overline{13}$ $\overline{14}$ $\overline{15}$ $\overline{19}$									
30A	X1A.$\overline{11}$ $\overline{13}$ $\overline{14}$ $\overline{15}$ $\overline{19}$									
32	X1.11									
32A	X1A.11									
33	X1.2	3.927								
33A	X1A.2	5.430								

List of variables used in multiple correlation analysis of daily snowmelt

Identification	Description of variable	Units	Identification	Description of variable	Units
X_1	Total runoff from 1 day's contribution to the hydrograph.	100 acre-feet.	X_{11}	Maximum temperature at headquarters.	10° F.
X_{1A}	First day runoff volume above recession.	10 acre-feet.	X_{12}	Degree-days above 40° F at headquarters.	° days.
X_2	Degree-days above 32° F at headquarters.	10° days.	X_{13}	Duration of temperature above 40° F at headquarters.	10 hours.
X_3	Degree-days above 50° F at headquarters.	° days.	X_{14}	Accumulated runoff April 1 to start of day plus recession in percentage of total runoff from April 1 to July 31.	10 percent.
X_4	Daily total solar radiation at Shadow Mountain.	100 Ly.			
X_5	Dew point temperature at headquarters.	10° F.	X_{15}	Daily wind travel at 23.1 feet in open.	10 mile.
X_6	Relative humidity at headquarters.	10 percent.	X_{16}	Daily wind travel at 1.4 feet in open.	10 mile.
X_7	Daily wind travel at 47.4 feet in open.	10 mile.	X_{17}	Degree-days above 32° F at windtower.	10° days.
X_8	Daily wind travel at 1.4 feet in forest.	10 mile.	X_{18}	Degree-days above 40° F at windtower.	10° days.
X_9	Daily wind travel at 24.9 feet in forest.	10 mile.	X_{19}	Relative humidity at windtower.	10 percent.
X_{10}	1000 to 1400 hour solar radiation at Shadow Mountain.	10 Ly.			

correlations using 1948 data—Continued

Independent variables—Continued									a	$\bar{R}$	Equation No.
X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}			
--------	--------	--------	.176	--------	--------	--------	--------	--------	−9.08	.62	22A
--------	--------	--------	--------	--------	--------	--------	--------	--------	−3.16	.52	23
--------	--------	--------	--------	--------	--------	--------	--------	--------	−9.35	.67	23A
--------	--------	--------	--------	--------	--------	--------	--------	--------	+3.93	.47	24
--------	--------	--------	--------	--------	--------	--------	--------	--------	−5.36	.59	24A
−.099	--------	9.295	--------	--------	--------	--------	--------	--------	−18.11	.70	25
3.444	--------	2.700	--------	--------	--------	--------	--------	--------	−21.96	.60	25A
--------	−.066	9.709	--------	--------	--------	--------	--------	--------	−18.52	.71	26
--------	.752	−.009	--------	--------	--------	--------	--------	--------	−7.54	.56	26A
--------	--------	--------	−.414	−.050	--------	--------	5.720	.570	−1.22	.48	27
--------	--------	--------	.143	.109	--------	--------	5.694	.686	−5.62	.70	27A
.806	--------	10.487	−.333	--------	--------	--------	--------	--------	−21.47	.76	28
2.787	--------	1.836	.241	--------	--------	--------	--------	--------	−19.52	.60	28A
--------	.217	9.724	−.363	--------	--------	--------	--------	--------	−18.05	.76	29
--------	.588	−.018	.212	--------	--------	--------	--------	--------	−7.81	.54	29A
.241	--------	11.383	−.286	.627	--------	--------	--------	1.077	−24.67	.81	30
2.528	--------	2.341	.263	.297	--------	--------	--------	.688	−23.05	.63	30A
1.559	--------	--------	--------	--------	--------	--------	--------	--------	−5.71	.28	32
3.261	--------	--------	--------	--------	--------	--------	--------	--------	−16.05	.64	32A
--------	--------	--------	--------	--------	--------	--------	--------	--------	−1.66	.50	33
--------	--------	--------	--------	--------	--------	--------	--------	--------	−3.19	.65	33A

Table 17—Summary of multiple

Equation No.	Dependent variable	Independent variables								
		X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
1	X1.26	3.005				−0.240				
1A	X1A.26	5.694				.475				
2	X1.27	2.938					0.155			
2A	X1A.27	4.464					.074			
3	X1.28	3.340						0.306		
3A	X1A.28	4.685						.087		
4	X1.247	2.886		0.049			.137			
4A	X1A.247	4.869		−.388			.217			
5	X1.257	2.997			−0.116		.136			
5A	X1A.257	3.717			1.440		.282			
6	X1.267	2.851				−.083	.132			
6A	X1A.267	5.336				.841	.308			
7	X1.268	3.054				−.184		.128		
7A	X1A.268	6.057				.885		.940		
8	X1.269	3.004				−.243			−.004	
8A	X1A.269	5.879				1.050			.752	
9	X1.467			−.124		−.887	.294			
9A	X1A.467			−.319		−.763	.614			
10	X1.67 $\overline{10}$					.013	.320			0.121
10A	X1A.67 $\overline{10}$					−.205	.621			.028
11	X1.7 $\overline{10}$ $\overline{19}$						.290			.112
11A	X1A.7 $\overline{10}$ $\overline{19}$						.650			.041
12	X1.7 $\overline{11}$ $\overline{13}$						.417			
12A	X1A.7 $\overline{11}$ $\overline{13}$						.213			
13	X1.7 $\overline{12}$ $\overline{13}$						.216			
13A	X1A.7 $\overline{12}$ $\overline{13}$						.127			
14	X1.7 $\overline{17}$ $\overline{19}$						.042			
14A	X1A.7 $\overline{17}$ $\overline{19}$						.226			
15	X1.$\overline{15}$ $\overline{17}$ $\overline{19}$									
15A	X1A.$\overline{15}$ $\overline{17}$ $\overline{19}$									
16	X1.$\overline{15}$ $\overline{18}$ $\overline{19}$									
16A	X1A.$\overline{15}$ $\overline{18}$ $\overline{19}$									
17	X1.$\overline{16}$ $\overline{17}$ $\overline{19}$									
17A	X1A.$\overline{16}$ $\overline{17}$ $\overline{19}$									
18	X1.2457	2.864		.057	.027		.136			
18A	X1A.2457	4.104		−.166	1.020		.283			
19	X1.2467	2.841		.014		−.079	.128			
19A	X1A.2467	5.298		−.060		.743	.303			
20	X1.2468	3.054		.040		−.136		.136		
20A	X1A.2468	6.082		.100		1.023		.976		
21	X1.267 $\overline{10}$	2.720				.512	.156			.103
21A	X1A.267 $\overline{10}$	5.324				.773	.300			−.008
22	X1.267 $\overline{14}$	6.673				.495	−.026			
22A	X1A.267 $\overline{14}$	5.240				.826	.312			
23	X1.3457		.172	.407	1.680		.339			
23A	X1A.3457		.358	.187	3.057		.521			
24	X1.3467		.284	−.240		−.578	.210			
24A	X1A.3467		.625	−.572		−.084	.428			

correlations using 1949 data

Independent variables—Continued									a	$\overline{R}$	Equation No.
X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}			
									+0. 97	0. 57	1
									−6. 91	. 81	1A
									−2. 16	. 57	2
									−2. 74	. 63	2A
									−1. 46	. 56	3
									−2. 38	. 80	3A
									−2. 13	. 54	4
									−2. 55	. 80	4A
									−1. 67	. 54	5
									−8. 56	. 81	5A
									−1. 24	. 54	6
									−12. 06	. 81	6A
									+. 38	. 54	7
									−11. 24	. 81	7A
									−2. 30	. 54	8
									−13. 39	. 82	8A
									7. 18	. 45	9
									4. 89	. 59	9A
									−2. 92	. 48	10
									−1. 50	. 58	10A
								−0. 101	−1. 62	. 48	11
								−. 060	−3. 11	. 58	11A
−0. 606		3. 965							−2. 71	. 54	12
. 496		4. 632							−7. 58	. 79	12A
	0. 097	2. 741							−3. 38	. 54	13
	. 182	4. 059							−4. 31	. 80	13A
						2. 769		−. 253	+1. 12	. 53	14
						5. 525		. 744	−10. 37	. 85	14A
				0. 050		2. 780		−. 246	1. 03	. 55	15
				. 195		5. 630		. 699	−9. 60	. 85	15A
				. 071			3. 644	+. 055	. 64	. 54	16
				. 210			7. 880	1. 188	−11. 28	. 84	16A
					. 095	2. 833		−. 221	. 87	. 55	17
					. 511	5. 867		. 922	−11. 73	. 86	17A
									−2. 27	. 51	18
									−6. 78	. 80	18A
									−1. 26	. 50	19
									−10. 95	. 80	19A
									−. 18	. 50	20
									−12. 82	. 80	20A
									−7. 93	. 43	21
									−11. 29	. 80	21A
			−. 631						−4. 93	. 64	22
			. 016						−11. 96	. 80	22A
									−8. 40	. 46	23
									−13. 45	. 76	23A
									−4. 92	. 45	24
									−4. 51	. 70	24A

Equation No.	Dependent variable	Independent variables								
		X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
25	$X1.67\,\overline{11}\,\overline{13}$					−.764	.238			
25A	$X1A.67\,\overline{11}\,\overline{13}$					.237	.269			
26	$X1.67\,\overline{12}\,\overline{13}$					−.497	.125			
26A	$X1A.67\,\overline{12}\,\overline{13}$					.660	.248			
27	$X1.\overline{14}\,\overline{15}\,\overline{18}\,\overline{19}$									
27A	$X1A.\overline{14}\,\overline{15}\,\overline{18}\,\overline{19}$									
28	$X1.67\,\overline{11}\,\overline{13}\,\overline{14}$					−.503	.077			
28A	$X1A.67\,\overline{11}\,\overline{13}\,\overline{14}$					.048	.385			
29	$X1.67\,\overline{12}\,\overline{13}\,\overline{14}$					.410	−.102			
29A	$X1A.67\,\overline{12}\,\overline{13}\,\overline{14}$					.528	.281			
30	$X1.\overline{11}\,\overline{13}\,\overline{14}\,\overline{15}\,\overline{19}$									
30A	$X1A.\overline{11}\,\overline{13}\,\overline{14}\,\overline{15}\,\overline{19}$									
32	X1.11									
32A	X1A.11									
33	X1.2	3.486								
33A	X1A.2	4.719								

List of variables used in multiple correlation analysis of daily snowmelt

Identification	Description of variable	Units	Identification	Description of variable	Units
X_1	Total runoff from 1 day's contribution to the hydrograph.	100 acre-feet.	X_{11}	Maximum temperature at headquarters.	10° F.
X_{1A}	First day runoff volume above recession.	10 acre-feet.	X_{12}	Degree-days above 40° F at headquarters.	° days.
X_2	Degree-days above 32° F at headquarters.	10° days.	X_{13}	Duration of temperature above 40° F at headquarters.	10 hours.
X_3	Degree-days above 50° F at headquarters.	° days.	X_{14}	Accumulated runoff April 1 to start of day plus recession in percentage of total runoff from April 1 to July 31.	10 percent.
X_4	Daily total solar radiation at Shadow Mountain.	100 Ly.			
X_5	Dew point temperature at headquarters.	10° F.	X_{15}	Daily wind travel at 23.1 feet in open.	10 mile.
X_6	Relative humidity at headquarters.	10 percent.	X_{16}	Daily wind travel at 1.4 feet in open.	10 mile.
X_7	Daily wind travel at 47.4 feet in open.	10 mile.	X_{17}	Degree-days above 32° F at windtower.	10° days.
X_8	Daily wind travel at 1.4 feet in forest.	10 mile.	X_{18}	Degree-days above 40° F at windtower.	10° days.
X_9	Daily wind travel at 24.9 feet in forest.	10 mile.	X_{19}	Relative humidity at windtower.	10 percent.
X_{10}	1000 to 1400 hour solar radiation at Shadow Mountain.	10 Ly.			

correlations using 1949 data—Continued

Independent variables—Continued									a	$\bar{R}$	Equation No.
X_{11}	X_{12}	X_{14}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}			
−1.307		4.322							8.08	.54	25
.714		4.521							−10.92	.78	25A
	−.013	3.158							1.22	.52	26
	.328	3.505							−10.42	.80	26A
			−.723	−.258			9.856	.815	−2.08	.65	27
			−.152	.141			9.183	1.370	−11.85	.84	27A
−.050		4.637	.323						−2.13	.63	28
−.195		4.293	.234						−6.42	.78	28A
	.518	3.186	−.596						−3.22	.59	29
	.251	3.501	.086						−9.78	.79	29A
−.101		4.657	−.312	.036				−.574	2.96	.55	30
−.189		4.388	.240	.427				.059	−6.70	.78	30A
1.864									−7.85	.48	32
2.707									−12.29	.73	32A
									−1.32	.59	33
									−2.33	.81	33A

Table 18—Summary of multiple correlations

Equation No.	Dependent variable	Independent variables								
		X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
1	X1.26	3.368				−0.116				
1A	X1A.26	5.684				.389				
2	X1.27	3.037					0.156			
2A	X1A.27	4.855					−.0003			
3	X1.28	3.377						0.360		
3A	X1A.28	4.833						.031		
4	X1.247	3.289		−0.208			.232			
4A	X1A.247	4.950		−.078			.028			
5	X1.257	2.813			0.432		.229			
5A	X1A.257	4.396			.876		.149			
6	X1.267	3.129				.094	.185			
6A	X1A.267	5.447				.598	.184			
7	X1.268	3.707				.219		.568		
7A	X1A.268	6.227				.924		.906		
8	X1.269	3.376				.004			0.206	
8A	X1A.269	5.698				.582			.331	
9	X1.467			−.302		−.822	.380			
9A	X1A.467			.267		−.051	.525			
10	X1.67 $\overline{10}$					−.189	.384			0.045
10A	X1A.67 $\overline{10}$					.118	.532			.080
11	X1.7 $\overline{10}$ $\overline{19}$						.362			.044
11A	X1A.7 $\overline{10}$ $\overline{19}$						.560			.084
12	X1.7 $\overline{11}$ $\overline{13}$						.344			
12A	X1A.7 $\overline{11}$ $\overline{13}$						.013			
13	X1.7 $\overline{12}$ $\overline{13}$						.234			
13A	X1A.7 $\overline{12}$ $\overline{13}$						.012			
14	X1.7 $\overline{17}$ $\overline{19}$						.125			
14A	X1A.7 $\overline{17}$ $\overline{19}$						.119			
15	X1.$\overline{15}$ $\overline{17}$ $\overline{19}$									
15A	X1A.$\overline{15}$ $\overline{17}$ $\overline{19}$									
16	X1.$\overline{15}$ $\overline{18}$ $\overline{19}$									
16A	X1A.$\overline{15}$ $\overline{18}$ $\overline{19}$									
17	X1.$\overline{16}$ $\overline{17}$ $\overline{19}$									
17A	X1A.$\overline{16}$ $\overline{17}$ $\overline{19}$									
18	X1.2457	3.375		−.229	−.078		.224			
18A	X1A.2457	3.882		.210	1.343		.154			
19	X1.2467	3.165		−.312		−.299	.165			
19A	X1A.2467	5.486		.250		.847	.146			
20	X1.2468	3.651		−.275		−.166		.471		
20A	X1A.2468	6.263		.326		1.361		1.003		
21	X1.267 $\overline{10}$	3.082				.254	.189			.028
21A	X1A.267 $\overline{10}$	5.367				.889	.192			.051
22	X1.267 $\overline{14}$	6.730				.623	−.024			
22A	X1A.267 $\overline{14}$	5.159				.555	.201			
23	X1.3457		.289	−.015	1.108		.425			
23A	X1A.3457		.424	.349	2.476		.332			
24	X1.3467		.379	−.506		−.594	.227			
24A	X1A.3467		.732	−.127		.380	.224			
25	X1.67 $\overline{11}$ $\overline{13}$					−.348	.249			
25A	X1A.67 $\overline{11}$ $\overline{13}$					.351	.108			
26	X1.67 $\overline{12}$ $\overline{13}$					−.174	.197			
26A	X1A.67 $\overline{12}$ $\overline{13}$					.682	.158			
27	X1.$\overline{14}$ $\overline{15}$ $\overline{18}$ $\overline{19}$									
27A	X1A.$\overline{14}$ $\overline{15}$ $\overline{18}$ $\overline{19}$									
28	X1.67 $\overline{11}$ $\overline{13}$ $\overline{14}$					−.088	.078			
28A	X1A.67 $\overline{11}$ $\overline{13}$ $\overline{14}$					.244	.179			
29	X1.67 $\overline{12}$ $\overline{13}$ $\overline{14}$					.582	−.043			
29A	X1A.67 $\overline{12}$ $\overline{13}$ $\overline{14}$					.591	.186			
30	X1.$\overline{11}$ $\overline{13}$ $\overline{14}$ $\overline{15}$ $\overline{19}$									
30A	X1A.$\overline{11}$ $\overline{13}$ $\overline{14}$ $\overline{15}$ $\overline{19}$									
32	X1.11									
32A	X1A.11									
33	X1.2	3.625								
33A	X1A.2	4.868								

using combined 1948 and 1949 data

Independent variables—Continued									a	$\bar{R}$	Equation No.
X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}			
									−0.26	0.59	1
									−6.11	.79	1A
									−2.20	.60	2
									.59	.79	2A
									−1.53	.60	3
									−2.43	.78	3A
									−2.09	.57	4
									−3.35	.81	4A
									−4.00	.59	5
									−6.08	.80	5A
									−3.25	.58	6
									−9.08	.79	6A
									−3.71	.58	7
									−11.61	.81	7A
									−1.67	.58	8
									−8.38	.79	8A
									6.91	.48	9
									−2.96	.55	9A
									−.26	.48	10
									−3.91	.56	10A
								−0.229	.26	.48	11
								.190	−4.86	.56	11A
−0.119		3.759							−4.40	.59	12
1.714		3.300							−10.94	.77	12A
	0.093	3.070							−3.81	.59	13
	.331	2.988							−2.66	.77	13A
						2.875		−.062	−1.05	.59	14
						5.327		.483	−7.09	.84	14A
				0.123		2.921		−.067	−.94	.59	15
				.130		5.361		.492	−7.19	.84	15A
				.109			3.736	.056	−.45	.57	16
				.072			7.302	.785	−6.73	.83	16A
					.248	3.151		.098	−2.34	.60	17
					.311	5.631		.727	−.18	.85	17A
									−2.83	.58	18
									−8.12	.79	18A
									1.33	.58	19
									−11.84	.79	19A
									.63	.58	20
									−16.62	.80	20A
									−5.02	.57	21
									−12.30	.79	21A
			−.572						−6.31	.66	22
			.046						−8.83	.79	22A
									−5.12	.53	23
									−10.42	.52	23A
									.98	.50	24
									−2.27	.70	24A
−.402		3.892							.43	.58	25
1.999		3.166							−15.81	.76	25A
	.055	3.228							−2.19	.58	26
	.480	2.368							−9.01	.78	26A
			−.566	−.252			8.084	.520	.01	.67	27
			−.043	.045			7.634	.820	−6.69	.82	27A
.644		4.734	−.350						−5.14	.62	28
1.567		2.818	.144						−13.51	.76	28A
	.497	3.588	−.540						−5.74	.66	29
	.427	2.325	.065						−8.59	.77	29A
.617		4.768	−.346	.079				−.107	−4.85	.62	30
1.553		.907	.147	.268				.346	−14.88	.77	30A
1.858									−7.76	.50	32
2.743									−12.57	.73	32A
									−1.38	.60	33
									−2.44	.79	33A

List of variables used in multiple correlation analysis of daily snowmelt

Identification	Description of variable	Units	Identification	Description of variable	Units
X_1	Total runoff from 1 day's contribution to the hydrograph.	100 acre-feet.	X_{11}	Maximum temperature at headquarters.	10° F.
X_{1A}	First day runoff volume above recession.	10 acre-feet.	X_{12}	Degree-days above 40° F at headquarters.	° days.
X_2	Degree-days above 32° F at headquarters.	10° days.	X_{13}	Duration of temperature above 40° F at headquarters.	10 hours.
X_3	Degree-days above 50° F at headquarters.	° days.	X_{14}	Accumulated runoff April 1 to start of day plus recession in percentage of total runoff from April 1 to July 31.	10 percent.
X_4	Daily total solar radiation at Shadow Mountain.	100 Ly.			
X_5	Dew point temperature at headquarters.	10° F.	X_{15}	Daily wind travel at 23.1 feet in open.	10 mile.
X_6	Relative humidity at headquarters.	10 percent.	X_{16}	Daily wind travel at 1.4 feet in open.	10 mile.
X_7	Daily wind travel at 47.4 feet in open.	10 mile.	X_{17}	Degree-days above 32° F at windtower.	10° days.
X_8	Daily wind travel at 1.4 feet in forest.	10 mile.	X_{18}	Degree-days above 40° F at windtower.	10° days.
X_9	Daily wind travel at 24.9 feet in forest.	10 mile.	X_{19}	Relative humidity at windtower.	10 percent.
X_{10}	1000 to 1400 hour solar radiation at Shadow Mountain.	10 Ly.			

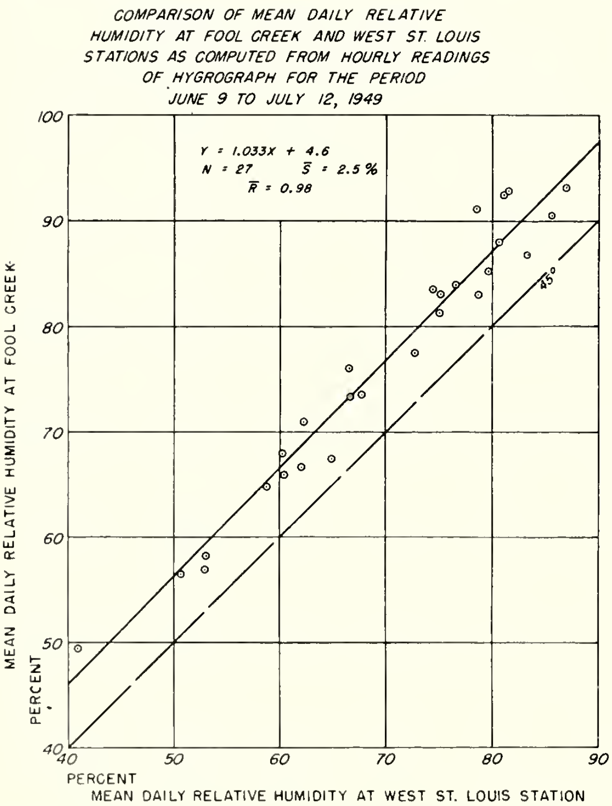


Figure 80. Comparison of relative humidity at Fool Creek and West St. Louis Creek Stations.

The correlation coefficients for the X_{1A}, first day's volume, are greater than for the total days' contribution to the snowmelt hydrograph, in the overwhelming number of cases.

The demonstration of a negative sign of the X_4 variable, daily total solar radiation, was an unlooked-for result, since it is known that the sun is the ultimate source of all energy used in snow melting. The physical explanation is that the effect of solar radiation is expressed to a rather full degree in the air temperature variable X_2 or X_3. Thus, in those equations where X_4 is used with X_2 or X_3, the solar radiation is effectively introduced twice. Ford [7] points out that, "A high correlation between independent variables may lead to illogical results, possibly to the extent of indicating relationships not in agreement with known physical behavior."

Because of time limitations, the analyses of the 1950 snowmelt season were limited to multiple correlation Equations 6 and 6-A and simple correlation Equations 32, 32–A, 33, and 33–A. Additional computations were made of Equations 32, 32-A, and 33, 33-A, for the day before and including the peak volume day. Results of the 1950 statistical computations are given in table 19. A solution of these ten equations, using the combined 1948, 1949, and 1950 data, is presented in table 20. Correlation coefficients for the equations prior to and including the peak volume day were found to be very much higher than for all of the days for the snowmelt season. Some difficulty was encountered with the hygrothermograph instruments during the 1950 snowmelt season, so the records, particularly those involving relative

[7] Reference 37, page 23.

Table 19—Comparison of correlations using all days with correlations using only days before and including day of greatest volume from 1950 data (all days)

Equation No.	Dependent variable	Independent variables X_2	X_6	X_7	X_{11}	a	$\overline{R}$	N
6	$X_{1.267}$	2. 202	0. 881	0. 717		−13. 40	0. 49	43
6A	$X_{1A.267}$	2. 705	. 397	. 703		−10. 34	. 72	43
32	$X_{1.11}$				1. 734	−8. 24	. 55	47
32A	$X_{1A.11}$				2. 214	−10. 40	. 72	47
33	$X_{1.2}$	2. 435				− . 62	. 43	43
33A	$X_{1A.2}$	3. 470				−1. 31	. 66	43
(Days Before and Including Peak Volume Only)								
32	$X_{1.11}$				2. 712	−13. 19	0. 87	34
32A	$X_{1A.11}$				3. 043	−14. 58	. 91	34
33	$X_{1.2}$	5. 001				−2. 77	. 88	30
33A	$X_{1A.2}$	5. 822				−3. 31	. 95	30

List of Variables Used in Correlation Analysis of Daily Snowmelt

Identification	Description of variable	Units
X_1	Total runoff from 1 day's contribution to the hydrograph.	100 acre-feet.
X_{1A}	First day runoff volume above recession.	10 acre-feet.
X_2	Degree-days above 32° F. at headquarters.	10° days.
X_6	Relative humidity at headquarters.	10 percent.
X_7	Daily wind travel at 47.4 feet in open.	10 mile.
X_{11}	Maximum temperature at headquarters.	10° F.

Table 20—Comparison of correlations using all days with correlations using only days before and including day of greatest volume from 1948, 1949, and 1950 (all days)

Equation No.	Dependent variable	Independent variables X_2	X_6	X_7	X_{11}	a	$\overline{R}$	N
6	$X_{1.267}$	2. 515	0. 675	0. 533		−10. 20	0. 53	88
6A	$X_{1A.267}$	3. 567	. 626	. 526		−10. 58	. 73	88
32	$X_{1.11}$				1. 704	−7. 44	. 52	92
32A	$X_{1A.11}$				2. 303	−10. 40	. 71	92
33	$X_{1.2}$	2. 782				−. 63	. 49	88
33A	$X_{1A.2}$	3. 893				−1. 47	. 70	88
(Days Before and Including Peak Volume Only)								
32	$X_{1.11}$				2. 595	−12. 07	0. 78	66
32A	$X_{1A.11}$				2. 920	−13. 78	. 85	66
33	$X_{1.2}$	5. 014				−2. 65	. 85	62
33A	$X_{1A.2}$	5. 513				−3. 11	. 90	62

List of Variables Used in Correlation Analysis of Daily Snowmelt

Identification	Description of variable	Units
X_1	Total runoff from 1 day's contribution to the hydrograph.	100 acre-feet.
X_{1A}	First day runoff volume above recession.	10 acre-feet.
X_2	Degree days above 32° F. at headquarters.	10° days.
X_6	Relative humidity at headquarters.	10 percent.
X_7	Daily wind travel at 47.4 feet in open.	10 mile.
X_{11}	Maximum temperature at headquarters.	10° F.

humidity and dewpoint temperatures, were not of the quality attained for the 1948-49 season, and the results of analyses involving these variables combining all the years of record may, therefore, be somewhat less reliable.

The indicated result of the statistical analysis of the factors causing snowmelt runoff lead to the conclusion that, for the data used in these cooperative snow investigations, the temperature factor is at least as good as, and in many cases better than a combination of other factors used in correlation analyses. Therefore, in the development or practical application of methods of forecasting runoff from snowmelt, particular attention was paid to the temperature variable, as will be discussed subsequently in this report.

A series of analyses for the runoff from Fool Creek, drainage area of 1.11 square miles, closely paralleling the above discussed analyses of the St. Louis Creek drainage basin runoff, were performed and will be presented in detail in section 12.

The finding that temperature alone is a very important and perhaps the most important factor in snowmelt is true for the high-altitude Rocky Mountain terrain such as that within which the Fraser Experimental Forest is found. It is known that high humidities, such as those which prevail in the coastal region of the Pacific Northwest, California Sierras, and in the northeastern United States, can have a very important influence upon the rate of snow melting, since for each gram of water condensed about 7 grams of ice can be melted due to the tremendous difference between the latent heat of vaporization of water and the latent heat of fusion of ice, as has been pointed out by Wilson [102]. The significance of the vapor content of the air as a factor affecting runoff from snowmelt and the disappearance of snow will be

considered in detail in section 10, dealing with Light's equation [64].

B. The physical approach to snowmelt

1. *General.* Practically all of the heat utilized in the melting of snow can be ascribed ultimately to solar radiation. Solar radiation may supply heat for snowmelt in several ways, among the principal ones being the following: (a) by direct incidence upon the snow; (b) by reflected radiation resulting from incidence of solar radiation upon objects with or without conversion from short-wave infrared to long-wave heat; and (c) indirectly as warm air, the temperature of which has been raised either by direct solar radiation or by contact with objects heated by the incidence of solar radiation or by the conversion of short-wave infrared solar radiation to long-wave heat. Another principal source of heat available for snowmelt, which is especially important in the coastal regions of the Pacific Northwest and of the Northeast, is the latent heat of vaporization which is released upon condensation of water vapor on snow. This can be considered as another source of solar energy for snow melting, since the initial transport of heat to the snow field by this mechanism was as a result of the solar energy used in evaporating the water, wherever that conversion to water vapor may have taken place.

The amount of heat released to the annual snowmelt by the cooling of the earth is negligible compared to that received by the earth as solar radiation. Temperatures of the soil below the snow during the snowmelt season are usually very close to the freezing point of water, indicating that practically no heat is supplied for snowmelt by the soil during the spring season.

In the physical approach to the analysis of snowmelt, use was made of the equation which expresses the physical relationship of wind, air temperature, and water vapor pressure as they interact to make heat available for the melting and evaporation of snow. The formula developed by Light [64] from Sverdrup's [83] eddy-conductivity equation involving a theory of atmospheric turbulence was chosen for use in this approach. Light's equation, both in general form and as reduced for application to the Fraser Experimental Forest data, is shown in figure 81.

PHILLIP LIGHT'S EQUATION

A. General statement:*

$$D = \frac{\rho k_0^2}{80 \ln(a/z_0)\ln(b/z_0)} U \left[c_p T + (e-6.11)\, 423/p\right]$$

in cgs units

D = effective snowmelt
ρ = density of air
k_0 = von Karman's coefficient = 0.38
ln = natural logarithm
a = elevation of anemometer in mb of hygrothermograph level
z_0 = roughness parameter = 0.25
b = elevation of hygrothermograph
U = wind velocity at anemometer level
c_p = specific heat of air at constant pressure = 0.24
T = air temperature at hygrothermograph level
e = vapor pressure of air
p = atmospheric pressure in mb

B. As reduced and applied to Fraser Experimental Forest data:

$$D = KU_M \left[0.00175(T_F - 32)10^{-0.0000156h} + 0.00550(e-6.11)\right]$$

D = effective snowmelt in inches per six hours
K = basin constant
U_M = average wind velocity in miles per hour at fifty foot level
T_F = average air temperature in degrees F. at 7.5 foot level
h = station elevation in feet above sea level
e = average vapor pressure in mb at 7.5 foot level
6.11 = vapor pressure in mb at 32° F. dew point

$$D = KU_M \left[0.0012(T_F - 32) + 0.0055(e - 6.11)\right]$$

* See reference 64

Figure 81. Light's equation.

In the application of Light's equation to the snowmelt and evaporation analysis, the data from only one installation were used, that of the windtower in the open. The wind records used in Light's equation were from the high-level anemometer at the top of the tower. Air temperatures and the vapor pressure data were from the hygrothermograph exposed at 7½ feet above the ground surface. The observations were corrected for height of instruments above the snow surface in accordance with the curves given by Light [64]. No attempt was made to use average temperatures or average humidities from other installations, since any endeavor to do so would introduce unknown complications in addition to making the system of doubtful utility to a practical hydrologist.

2. *Distribution of wind with height.* A necessary condition for the application of Light's eddy-conductivity equation, as shown in figure 81, in which wind velocity at only one level is introduced in the reduced form of the equation, is that there exists a logarithmic distribution of wind velocity with height. The wind records from anemometers at three levels at the windtower in the open were analyzed for the 1948 snowmelt runoff period, and the results of a plotting of the miles of wind total for 6-hour periods, May 19 to May 22, 1948, are shown in figure 82. This chart shows a definite logarithmic relationship of wind velocity distribution and height.

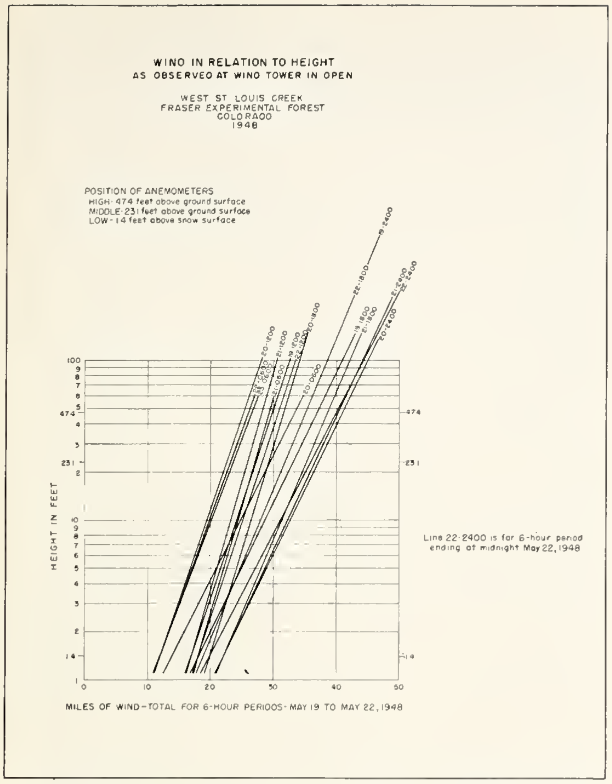


Figure 82. Six-hour wind in relation to height at wind-tower in open, 1948.

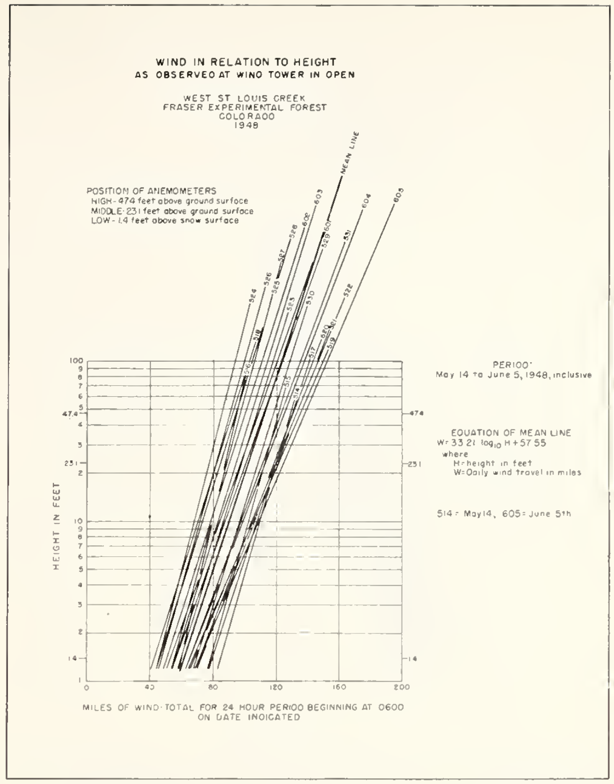


Figure 83. Daily wind in relation to height at wind-tower in open, 1948.

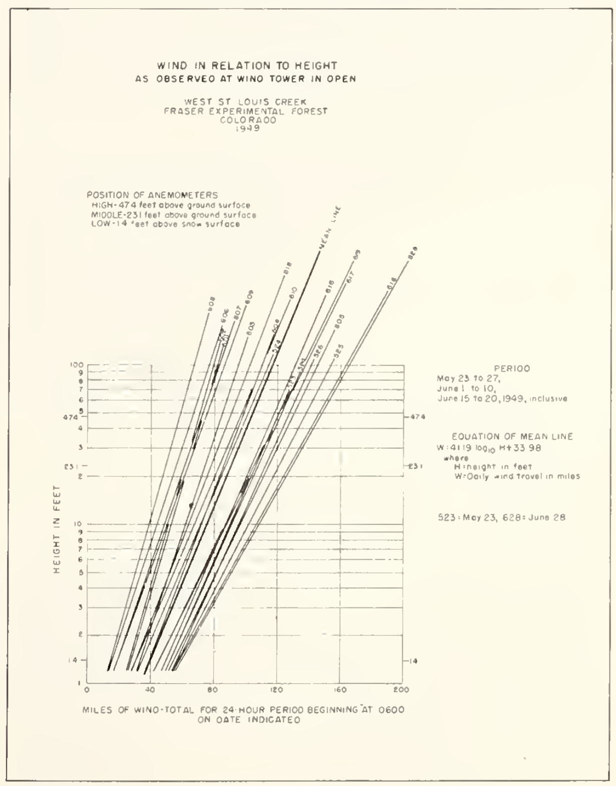


Figure 84. Daily wind in relation to height at wind-tower in open, 1949.

Miles-of-wind totals for 24-hour periods beginning at 6 a. m. on the date indicated were plotted for 1948, 1949, and 1950 snowmelt seasons, as shown, respectively, in figures 83, 84, and 85. The equations of the mean lines for the 1948, 1949, and 1950 seasons analyses of 24-hour wind velocity distribution in relation to height are summarized in the following three equations in which it will be noted that the equations for 1948 and 1950 are practically identical, while the equation for 1949 does not deviate very far from the slope of the other two equations:

For 1948, $W=33.21 \log_{10}H+57.55$

For 1949, $W=41.19 \log_{10}H+33.98$

For 1950, $W=33.34 \log_{10}H+60.13$

In the above equations, W equals the daily wind travel in miles and H is height in feet at the anemometers as follows: The high anemometer was 47.4 feet above the ground surface; the middle anemometer was 23.1 feet above the ground surface; and the low anemometer was 1.4 feet above the snow surface on the date of observation. The miles of wind are the totals for a 24-hour period beginning at 6 a. m. on the date indicated. Not only the mean lines, but the individual lines, on the charts, figures 82, 83, 84, and 85, disclose

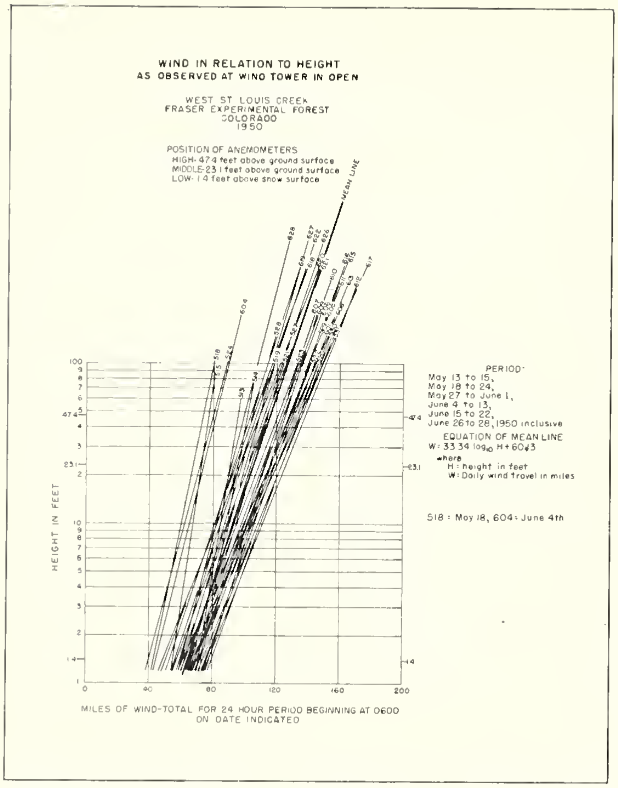


Figure 85. Daily wind in relation to height at windtower in open, 1950.

the requisite logarithmic distribution of wind velocity above the surface, thus meeting the requirement of Light's equation insofar as the wind factor is concerned.

3. *Application of Light's equation.* Air temperature data from the hygrothermograph at the windtower in the open were used in Light's equation directly without adjustment for lapse rate within the Fraser Experimental Forest. No lapse rate adjustment was made, since observations in the field, even prior to those substantiated by the 1950 snow disappearance study discussed previously, had disclosed that, although snow accumulation ordinarily takes place by elevation zones, snow disappearance in a mountainous region takes place chiefly by aspects. Any endeavor to apply lapse rate correction by aspects would so complicate the computation of the temperature factor in Light's equation as to throw serious doubt on its acceptability in applied hydrology.

Vapor pressure required for Light's equation was computed from the hygrothermograph trace in a manner discussed in detail in a subsequent section on instruments. The computational procedure for deriving a day's snowmelt by Light's equation for St. Louis Creek is illustrated in table 21, in which Light's equation is finally reduced to the following simple form:

$$D=U_M[0.0012(T_F-32)+0.00550(e-6.11)]$$

It will be noted that 6-hour periods, for which negative melts are computed, are not included in the daily total.

The results of the application of Light's equation to snowmelt runoff for the 1948, 1949,

Table 21—Example of computation of snowmelt by Light's equation

$D=U_M\ [0.00175^*(T_F-32)10-{}^{.0000156h}+0.00550^*(e-6.11)]$

Where: D = effective snowmelt in inches per six hours
U_M = average wind velocity in miles per hour —50′ level
T_F = air temperature in degrees Fahrenheit
e = vapor pressure in millibars
h = station elevation above sea level in feet (10,500′)

Substituting value of *h* and reducing:

$D\ = U_M\ [0.00175(TF-32)0.6858+0.00550(e-6.11)]$
$\ \ = U_M\ [0.0012(T_F-32)+0.00550(e-6.11)]$

Date 1948	6-hour period ending at		Total for 24-hour period	Effective date with time lag for St. Louis Creek
May 14	6 a. m	Example of substitution of values: $D=4.67\ [0.0012(37.12-37)+0.00550(3.15-6.11)]$ $D=4.67(0.0062-0.0163)=-0.047.$		
	12 noon	$D=7.00(0.0274-0.0170)=0.073.$		
	6 p. m	$D=5.83(0.0266-0.0144)=0.071.$		
	12 midnight	$D=5.33(0.0-0.0043)=-0.023.$		
May 15	6 a. m	$D=3.50(-0.0038-0.0144)=-0.064$	0. 144	May 14
	12 noon	$D=5.17(0.0236-0.0178)=0.030$		
	6 p. m	$D=4.83(0.0248-0.0163)=0.041$		
	12 midnight	$D=6.67(-0.0020-0.0083)=-0.069$		

*Constants have been corrected because the temperature and relative humidity are measured at about the 7.5′ instead of 10′ level.

and 1950 snowmelt seasons are given, respectively, in tables 22, 23, and 24, in which the melt computed by Light's equation is compared with the runoff volume as measured from the hydrograph, including the recession contribution as described previously.

Because of the marked change in the characteristics of the runoff from snowmelt following the day of peak volume of contribution, including the recession, the basin constants in this series of three tables were computed only for the days through the day of largest volume contribution for use in comparison of the observed snowmelt runoff with that computed by Light's equation. The results of the basin constant computation are: For 1948, 0.901; for 1949, 0.993; for 1950, 0.954. The basin constant is simply a ratio consisting of the snowmelt volume as measured from the hydrograph divided by the melt computed from Light's equation. Table 25 presents a comparison of the basin constants for Light's equation for the three years. Three sets of coefficients are

Table 22—Comparison of snowmelt computed from Light's equation with recorded runoff volumes, 1948

Date	Melt computed by Light's equation	Runoff volume as measured from hydrograph [1]	Departure of computed from measured volume	
	Inch	*Inch*	*Inch*	*Percent*
May 14	0.144	0.336	−0.192	−57
15	.071	.186	−.115	−62
16	.134	.231	−.097	−42
17	[2].294	.303	−.009	−3
18	.376	.274	.102	37
19	.487	.278	.209	75
20	.369	.392	−.023	−6
21	.422	.320	.102	32
22	.258	.224	.034	15
23	.167	.162	.005	3
24	.220	.106	.114	108
25	.216	.178	.038	21
26	.157	−.029	.186	641
27	.208	.319	−.111	−35
28	.168	.167	.001	1
29	.119	.125	−.006	−5
30	.455	.358	.097	27
31	.439	.290	.149	51
June 1	.491	.462	.029	6
2	.524	.339	.185	55
3	.262	.276	−.014	−5
4	.207	.148	.059	40
5	.379	.207	.172	83
Total	6.567	5.652	0.915	16.2
Total through June 1	5.195	4.682	0.513	11.0

Basin constant (through June 1) = K = 4.682/5.195 = 0.901.

[1] Includes recession flow.
[2] Air temperature and relative humidity estimated for two hours.

Table 23—Comparison of snowmelt computed from Light's equation with recorded runoff volumes, 1949

Date	Melt computed by Light's equation	Runoff volume as measured from hydrograph [1]	Departure of computed from measured volume	
	Inch	*Inch*	*Inch*	*Percent*
May 19	0.035	0.060	−0.025	−42
20	.004	.001	.003	300
21	.046	0	.046	-------
22	.042	.025	.017	68
23	.076	.066	.010	15
24	.173	.113	.060	53
25	.150	.198	−.048	−24
26	.293	.262	.031	12
27	.292	.167	.125	75
28	[2].174	.222	−.048	−22
29	[2].219	.099	.120	121
30	[2].144	.149	−.005	−3
31	[2].053	−.025	.078	312
June 1	.012	−.039	.051	131
2	.033	−.001	.034	3,400
3	.112	.116	−.004	−3
4	.167	.187	−.020	−11
5	.326	.340	−.014	−4
6	.137	.102	.035	34
7	.187	.069	.118	171
8	.195	.380	−.185	−49
9	.221	.204	.017	8
10	.246	.239	.007	3
11	[2].377	.515	−.138	−27
12	[2].341	.668	−.327	−49
13	[2].358	.221	.137	62
14	[2].141	.107	.034	32
15	.340	.451	−.111	−25
16	.774	.732	.042	6
17	.704	.364	.340	93
18	.361	−.132	.493	373
19	.499	.347	.152	44
20	.492	.203	.289	142
Total	7.724	6.410	1.314	20.5
Total through June 16	5.668	5.628	0.040	0.7

Basin constant (through June 16) = K = 5.628/5.668 = 0.993.

[1] Includes recession flow.
[2] Daily and 6-hourly distribution of wind travel was estimated. Total wind travel for these periods was determined from totalizing anemometer.

given: one for the period prior to and including the day of the largest volume; another for the period after the day of the largest volume; and a third, the total for the days used in the analysis. The values of these basin constants, based upon the three years of data, turned out to be strikingly different for the three periods, although there is a close agreement between years. The 3-year averages for the period through the day of the largest volume was found to be 0.951 and for the period after the day of the largest volume, 0.323; and the average for all days was found to be 0.734 for the constant of Light's equation.

4. Comparison of basin constant K. Light's equation basin "constant," K, as used in a study

Table 24—Comparison of snowmelt computed from Light's equation with recorded runoff volumes, 1950

Date	Melt computed by Light's equation	Runoff volume as measured from hydrograph [1]	Departure of computed from measured volume	
	Inch	*Inch*	*Inch*	*Percent*
May 13	0.025	0.106	−0.081	−76
14	.090	.174	−.084	−48
15	.129	.025	.104	416
16	[2].093	.174	−.081	−47
17	[2].262	.156	.106	68
18	.088	−.035	.123	351
19	.007	.054	−.047	−87
20	.009	.103	−.094	−91
21	.095	.216	−.121	−56
22	.217	.193	.024	12
23	.309	.188	.121	64
24	.284	.012	.272	2,267
25	0	−.020	.020	100
26	0	−.086	.086	100
27	.035	.010	.025	250
28	.146	.053	.093	175
29	.072	.050	.022	44
30	.458	.280	.178	64
31	.212	.306	−.094	−31
June 1	.129	.364	−.235	−65
2	.266	.298	−.032	−11
3	0	−.209	.209	100
4	.018	.101	−.083	−82
5	.298	.328	−.030	−9
6	.363	.558	−.195	−35
7	.265	.235	.030	13
8	.021	−.065	.086	132
9	.127	.349	−.222	−64
10	.396	.532	−.136	−26
11	.409	.496	−.087	−18
12	.415	.310	.105	34
13	.468	.399	.069	17
14	.496	.348	.148	43
15	.854	.729	.125	17
16	.902	.620	.282	45
17	.428	.124	.304	245
18	.310	−.224	.534	238
19	.355	.088	.267	303
20	.263	.119	.144	121
21	.452	.094	.358	381
22	.426	.039	.387	992
23	.463	.116	.347	299
24	.578	.076	.502	661
25	.344	−.018	.362	2,011
26	.470	.047	.423	900
27	.510	.083	.427	514
28	.553	.144	.409	284
Total	13.110	8.040	5.067	63.0
Total through June 15	7.056	6.732	0.322	4.8

Basin constant (through June 15) = K = 6.732/7.056 = 0.954

[1] Includes recession flow.
[2] Wind travel for these days estimated.

of the maximum possible precipitation in the Sacramento River Basin, California [89], was considered as reflecting the surface characteristics of a basin or region and was assumed to remain constant for all ranges of wind velocity, temperature, humidity, and elevation. The

Table 25—Summary of basin constants in Light's equation as computed from runoff volumes including recession

Year	Period		Number of days	Melt computed by Light's equation (inches)	Runoff volume measured from hydrograph (inches)	Basin constant K
1948	Before and including day of largest volume		19	5.195	4.682	0.901
	After day of largest volume		4	1.372	.970	.707
	Total for season		23	6.567	5.652	.861
1949	Before and including day of largest volume		29	5.668	5.628	.993
	After day of largest volume		4	2.056	.782	.380
	Total for season		33	7.724	6.410	.830
1950	Before and including day of largest volume		34	7.056	6.732	.954
	After day of largest volume		13	6.054	1.308	.216
	Total for season		47	13.110	8.040	.613
Averages 1948–49–50	Unweighted average of K's.	Before				.949
		After				.434
		Total				.768
	Weighted by number of days.	Before				.956
		After				.341
		Total				.738
	Using total volumes for 3 years.	Before		17.919	17.042	0.951
		After		9.482	3.060	.323
		Total		27.401	20.102	.734

Table 26—Computation of basin constant in Light's equation as computed from daily discharges for 1948

St. Louis Creek, near Fraser, Colo.

Date	Average (c. f. s.)	Stream flow (inches depth per day)	Light's equation (inches)
May 14	35	0.040	0.144
15	49	.056	.071
16	59	.067	.134
19	100	.113	.487
20	113	.127	.369
21	135	.153	.422
22	150	.170	.258
23	148	.169	.167
24	140	.159	.227
27	131	.148	.208
28	142	.161	.168
29	138	.156	.119
30	145	.164	.455
31	160	.181	.439
June 1	170	.193	.491
Totals		2.057	4.159

$$K_1 = \frac{2.057}{4.159} = 0.495$$

Light's equation constant K, as used in the Fraser Forest investigation, is not considered to be a correction factor for watershed characteristics, since those are integrated in the recession analysis concept as explained in section 7 of this report.

In order to compare the two concepts with regard to the meaning of the K in Light's equation, a computation was performed for the 1948, 1949, and 1950 snowmelt seasons of a basin constant for Light's equation using actual daily discharges as recorded at the St. Louis Creek gaging station rather than the day's contribution to the snowmelt hydrograph, including the recession flows. Table 26 is the computation for 1948, based upon runoffs from Reference 91. Table 27 shows the computations for 1949, using runoffs from Reference 92, and table 28 is the table for 1950, using runoffs from Reference 93.

The value of the Light's equation K as computed in this manner was found to be 0.495 for the 1948 season, 0.470 for the 1949 season, and 0.511 for the 1950 snowmelt season.

The runoff volumes used in Reference 89 were computed by including a correction for base flow and time distribution of melt obtained by correcting the increments of runoff for channel storage by the method of Langbein involving the use of storage discharge curves for the basin [62].

Table 27—Computation of basin constant in Light's equation as computed from daily discharges for 1949

St. Louis Creek, near Fraser, Colo.

Date	Average (c. f. s.)	Stream flow (inches depth per day)	Light's equation (inches)
May 23	40	0.045	0.076
24	43	.049	.173
25	51	.058	.150
26	64	.073	.293
27	75	.085	.292
June 1	80	.091	.012
2	73	.083	.033
3	69	.078	.112
4	78	.088	.167
5	90	.102	.326
6	96	.109	.137
7	90	.102	.187
8	90	.102	.195
9	110	.125	.221
10	110	.125	.246
15	187	.212	.340
16	220	.227	.774
Totals		1.754	3.734

$$K_1=\frac{1.754}{3.734}=0.470$$

Table 28—Computation of basin constant in Light's equation as computed from daily discharges for 1950

St. Louis Creek, near Fraser, Colo.

Date	Average (c.f.s.)	Stream flow (inches depth per day)	Light's equation (inches)
May 13	24	0.027	0.025
14	27	.031	.090
15	30	.034	.129
18	45	.051	.088
19	42	.048	.007
20	45	.051	.009
21	55	.062	.095
22	65	.074	.131
23	74	.084	.309
24	77	.087	.284
27	51	.058	.035
28	52	.059	.146
29	52	.059	.072
30	59	.067	.458
31	79	.030	.212
June 1	96	.109	.129
4	92	.104	.018
5	102	.116	.298
6	135	.155	.363
7	158	.179	.265
8	140	.159	.021
9	135	.153	.127
10	160	.181	.396
11	188	.213	.409
12	209	.237	.415
13	212	.240	.468
15	230	.261	.854
Totals		2.989	5.853

$$K_1=\frac{2.989}{5.853}=0.511$$

The values of the basin constant, as computed in Reference 89 are given in the following table:[8]

Basin	*Area (square miles)*	*Basin constant*
Middle Fork of Yuba at Milton	41	0.75
North Fork of Yuba at Sierra City	91	.51
Middle Fork of Yuba near N. San Juan	207	.67
		Average
		0.6

Reference 89 ascribes the differences in the values of the basin constant to errors involved in runoff analysis and in the estimates of the snow-covered area from the meager number of snow depth measurements. Another possibility considered was that the differences were real and represent variations in basin characteristics. In the absence of detailed analyses on topography, forest cover, etc., for the three basins, Reference 89

[8] Reference 89, page 170.

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decided to adopt an average value for the Light's equation basin constant and to consider this as applicable throughout the Sacramento River drainage basin.

A comparison of the values of the basin constant from the Yuba River and the Light's equation constant as derived for St. Louis Creek when compared on this basis, shows relatively small differences between the two values. This comparison indicates that the manner of computation of a day's contribution to the snowmelt hydrograph and the analysis of the hydrograph is critical in deciding the numerical value of Light's equation constant. As derived by Light [64], the constant should be unity when applied to a smooth snow field. However, the results of the Fraser Experiment Forest study show the constant to be practically unity even on the well-forested watershed of St. Louis Creek when the melt from Light's equation is related to total volume of runoff from each day's melt during the period when there is snow available. It is to be noticed that Light's equation does not include a factor for direct solar radiation.

SECTION 10—EVAPORATION DURING THE SNOWMELT SEASON

A. Review of previous works

The phenomenon of evaporation of snow has been the subject of numerous investigations, either directly aimed at an evaluation of the magnitude of such loss or as a corollary to investigations primarily conducted for other purposes. Thus, evaporation from snow is touched upon in References 11, 12, and 36. The complexities of the problem are such that there has not as yet been attained a wholly satisfactory evaluation of evaporation losses directly from snow, since the technique used in the investigation tends to influence the magnitude of the answer. In the following discussion of previous work on this subject, it should be kept in mind that the references deal with evaporation from a snow surface as distinct from evapotranspirational loss from a drainage basin on which snow is actively melting.

Church [21], in reporting on progress of the Mount Rose Observatory, Nevada, 1906–12, discussed the importance of evaporation loss to the conservation of snow. He reported that timber screens, by checking the wind, would tend to reduce the evaporation of snow which, under the influence of the wind movement of 33 miles per hour, and despite the fact that the snow was frozen, reached in a single night a total of 0.10 inch of moisture content.

A study of evaporation from snow was performed by the Forest Service during the 1940, 1941, and 1942 snowmelt periods at the Fraser Experimental Forest. The special installation and a discussion of results were reported by Wilm and Dunford [101] and by Wilm and Connaughton [100].

Baker [6] performed a series of experiments on evaporation from snow surfaces in Utah in the winter and spring of 1915–16 over a period of about 180 days. The snow-water equivalent for the same locality for the winter of 1915–16 was 21.91 inches, from which, according to Baker's measurements, ±3 inches of evaporation occurred as measured by two different methods. Thus, Baker's measurements of evaporation indicated that about 14 percent of the total snowfall was evaporated into the air. It is noted that Baker made no measurement during periods of storms, high winds, or during the spring thaw period. The evaporation losses from the snow, as reported by Baker, were based upon measurements during calm, clear days during the winter only.

Baker refers to the work of Rolf [80] who described his investigations in Lapland and developed a formula which, according to Baker, gave results of between one-third and one-half of those actually measured by Baker at the Utah Experiment Station.

Kaitera [57] reported upon a field investigation conducted in Finland during the spring of 1937 and 1938, using pans having an area of 500 square centimeters. Kaitera observed that when the temperature of the air rises, evaporation seems to decrease. This observation of Kaitera is substantiated by additional references to be included below and by the computations performed on the Fraser Experimental Forest data.

Croft [28] described a study of evaporation which was conducted for a 10-day record, 6 of which were complete, from snow under 3 site conditions, including full insolation and free air movement; shade with free air movement; and full shade with no air movement on a drainage basin in the Wasatch Plateau in central Utah. Cones of snow 6 inches in diameter and 6 inches deep were used. Records of temperature of the snow surface, wet- and dry-bulb temperatures at ½ foot, 4½ feet, and 12 feet above the snow surface and wind speeds at ½ foot and 4½ feet above the snow surface were observed. Vapor pressures were calculated. Neither shade nor mean daily air temperatures were found to be related to evaporation, but air movement and evaporation were very closely related. Differences in vapor pressure of snow and air were found to be very significant in relation to snow evaporation losses. Converting Croft's data to monthly losses, the results indicate that the average for his study would amount to

about 1.2 inches per month. The loss for the highest days of evaporation would be the equivalent of about 1.6 inches per month. Where air movement was prevented, the equivalent loss would amount to about 0.7 inch per month.

De Quervain [30], as translated by McClain, reported upon evaporation from the snow pack investigation conducted in the vicinity of Davos, Switzerland, as part of the investigations of the Swiss Institute for Snow and Avalanche Research. Some of the results of De Quervain's study converted into the English system are given in the subparagraphs below:

March 9, 1950, from 9 a. m. to 5 p. m.

Weissfluh summit, feet	*Research field at Weissfluhjoch, feet*	*Town square at Davos, feet*
9, 350	8, 333	5, 085
Average evaporation in grams per square centimeter per hour		
82. 1	60. 5	27. 0
Converting the above rates of evaporation to inches' depth of evaporation for the day		
0. 0259	0. 0191	0. 0085

June 9, 1950, between 8: 23 a. m. and 3: 35 p. m., a condensation of 0.0212 inch was observed.

Diamond [32] computed, using Sverdrup's equation [83], the snowmelt and snow evaporation potentialities for a series of assumed conditions of air temperature, relative humidity, vapor pressure, wind velocity, and snow surface temperature. His computations show that significant amounts of evaporation from snow occur at low temperatures, not far above freezing, when the vapor pressure gradient is from snow to the air. At higher temperatures and relative humidities, snowmelt tends to exceed by far the loss by evaporation. The results of the computation of evaporation by Light's equation, to be subsequently presented in this section, support Diamond's conclusions, as likewise do the observations of Kaitera [57]. The Fraser Forest investigation results, to be presented subsequently, show greater proportionate evaporation in May than in June in relation to melt for each of the 3 years for which data were available for such detailed analyses.

Kittredge presents a very comprehensive analysis of evaporation in the ponderosa-sugar pine-fir zone of the central Sierra Nevada in California. Kittredge [61] is quoted as follows:

> The outstanding characteristic of the evaporation studies in the present work on the west slope of the Sierra Nevada is the small magnitude of the measured losses. The explanation is probably to be found in the geographic and physiographic location on the west-facing slopes of the mountains which are exposed to the moisture-bearing winds of the Pacific Ocean. Thus, the humidity of the atmosphere is high, and the vapor pressure difference between snow surface and air above tends to be low or negative; consequently, the evaporation is also low.
>
> The question has been raised as to whether it is possible to obtain a reliable measure of evaporation from snow by the use of any container in view of the fact that solar radiation penetrates 5 inches or more through the snow and thus tends to heat the walls of the container. This heat would be transmitted to the snow in the container and would obviously accelerate melting.

Kittredge summarizes a computation of evaporation (for the season of 1935 in an opening in mature ponderosa pine made by using Horton's formula for a free-water surface in the Weather Bureau pan in which values were used of air temperature at 4 feet, relative humidity, wind velocity, and snow temperature at the 3-inch depth, and vapor pressure difference between the air and at the snow surface) as follows for each of the months: January, 0:51 inch; February, 0.54; March, 0.63; April, 0.33; and May, minus 0.03. The negative sign means that for May 1935, condensation exceeded evaporation by 0.03 of an inch. Air temperatures and relative humidities prevailing for the period reported are as follows: January 1935, air temperature 29°, relative humidity 82 percent; February, 33° and 76 percent; March, 31° and 77 percent; April, 40° and 76 percent; and May, 43° and 75 percent.

Kirschmer and Rimkus [59] constructed weighing lysimeters with an exposed area of 6¼ square meters for the direct measurement of snow disappearance by weight. The snowmelt was caught in receptacles in a pit under the lysimeter pan. Taking into consideration the experiences of numerous other investigators, it is easy to understand why Kirschmer and Rimkus came to the surprising result that snow evaporation is essentially zero. They concluded that the gradual reduction of the snow cover during the winter is not due to evaporation but to continual melting of the bottom layers, since even at air temperatures of 30° below zero C, the earth under the snow cover shows a temperature slightly above 0° C. They concluded also that the volume of mountain stream floods is not proportional to the total amount of winter snowfall. This is indeed a surprising series of conclusions, which were directed to a great extent by the equipment and the techniques used. The conclusions of the two investigators have not been sub-

stantiated elsewhere, especially their conclusion that the melting of snow occurs from the bottom of the pack rather than from the top. This reference was included to indicate the complexity of this facet of cryologic hydrology.

The melting of snow from the top has been proven by numerous investigators through the use of dyes, such as fuchsin, which remains a black powder in the presence of dry ice crystals but changes to an intense purple solution in the presence of water. Its use permits the tracing of melt waters both vertically and horizontally through the snow packs and the technique has been used extensively to follow the progress of the ripening of the snow pack and the release of water from the melted snow.

B. Calculation of evaporation losses through Light's equation

Light's equation permits differentiation between snow melting and snow evaporation. If the value of e, the average vapor pressure in millibars, in the expression: $(e-6.11)$ is less than 6.11, the expression becomes negative, indicating evaporation. If the air temperature is less than 32° F, the expression: (T_f-32) becomes negative. When this occurs, the 6.11 may need to be changed to the value corresponding to the actual temperature of the snow surface. The interrelationships of temperature and vapor pressure of ice at temperatures below the freezing point with relative humidity of the air are very intricate, and theoretical considerations and field observations indicated that at temperatures below 32° F, very little evaporation of snow can occur. When the mean air temperature is less than the snow surface temperature, there is no heat transfer from the air to the snow, and the only major source of heat for both evaporation and melting is solar radiation. Since snow has a very high reflectivity for short-wave radiation without its being converted to long-wave sensible heat, appreciable evaporation will occur only when there is turbulent transfer of heat from air to the snow. Diamond [32] presents a number of charts illustrating this interrelationship.

In Light's equation, computation of evaporation using the Fraser Experimental Forest data were therefore made, both including periods when average temperature was below 32° F and excluding periods having average temperature below 32° F. As is to be expected, the evaporation indicated for the periods including those temperatures below 32° F was a little greater than that excluding such periods. A summary of the evaporation losses for each of the 3 years subjected to intensive analysis is presented in tables 29, 30, and 31 for the 1948, 1949, and 1950 snowmelt seasons, respectively.

Table 29—Evaporation from snow computed by Light's equation, 1948

St. Louis Creek, near Fraser, Colo.

Total inches for 24-hour period beginning at 0600 on date shown [1] (using basin constant K=1)

Date	Exclusive of periods having average temperature below 32° F	Including periods of average temperature below 32° F [2]
May 14 [3]	0. 226	0. 276
15 [3]	. 171	. 276
16	. 164	. 164
17 [4]	. 084	. 084
18	. 011	. 011
19	None	None
20	. 071	. 071
21	. 095	. 095
22 [3]	. 163	. 182
23	. 039	. 039
24	. 018	. 018
25 [3]	. 011	. 038
26 [3]	. 020	. 031
27	. 061	. 061
28	. 027	. 027
29 [3]	. 148	. 170
30	. 062	. 062
31	. 038	. 038
June 1	. 013	. 013
2	None	None
3	. 122	. 122
4	. 186	. 186
5	. 130	. 130
Total	1. 860	2. 094
Total through June 1	1. 422	1. 656

[1] Sum of evaporation for four 6-hour periods.
[2] Not corrected for change in vapor pressure of snow surface due to possible lowering of snow surface temperature when 6-hour average air temperature is below 32° F.
[3] Days in which there is at least one 6-hour period having average temperature below 32° F.
[4] Air temperature and relative humidity estimated for two hours.

Since the basin constant was computed only to express the relationship between actual runoff and runoff computed by Light's equation, no basin constant was applied to the theoretically computed evaporation losses, as there exists no reference standard which could be used to derive a constant with regard to evaporation from the snow. Paralleling the relationships computed for snowmelt by Light's equation, tables 29, 30, and 31 present totals not only for the whole period of analysis but also through the day of largest volume contribution to the snowmelt runoff.

A summary of evaporation, as computed by Light's equation, exclusive of periods having average temperatures below 32° F, is presented in table 32. The average evaporation, as computed by

Table 30—Evaporation from snow computed by Light's equation, 1949

St. Louis Creek, near Fraser, Colo.

Total inches for 24-hour period beginning at 0600 on date shown [1] (using basin constant K=1)

Date	Exclusive of periods having average temperature below 32° F	Including periods of average temperature below 32° F [2]
May 19 [3]	0. 151	0. 237
20	. 174	. 174
21 [3]	. 022	. 026
22	. 044	. 044
23 [3]	. 161	. 167
24 [3]	. 143	. 159
25 [3]	. 166	. 167
26 [3]	. 108	. 114
27	. 036	. 036
28 [4]	None	None
29 [3 4]	. 042	. 052
30 [3 4]	. 182	. 187
31 [3 4]	. 168	. 187
June 1 [3]	. 038	. 060
2 [3]	. 094	. 102
3	. 059	. 059
4	None	None
5	. 085	. 085
6	None	None
7	None	None
8	None	None
9	None	None
10	. 006	. 006
11 [4]	None	None
12 [4]	None	None
13 [4]	None	None
14 [4]	. 098	. 098
15	. 112	. 112
16	. 011	. 011
17	None	None
18	None	None
19	. 031	. 031
20	. 126	. 126
Total	2. 057	2. 240
Total through June 16	1. 900	2. 083

[1] Sum of evaporation for four 6-hour periods.
[2] Not corrected for change in vapor pressure of snow surface due to possible lowering of snow surface temperature when 6-hour average air temperature is below 32° F.
[3] Days in which there is at least one 6-hour period having average temperature below 32° F.
[4] Daily and 6-hourly distribution of wind travel was estimated. Total wind travel for these periods was determined from totalizing anemometer.

Light's equation, for 50 days in May 1948, 1949, and 1950 is 0.096 inch per day. The average for 32 days of June 1948, 1949, and 1950 is 0.069 inch per day. The average evaporation per day, as computed by Light's equation, for a a grand total of 82 days for the 3 seasons, is 0.086 inch per day for the days including the day of largest volume contribution to the snowmelt runoff.

Figures 86, 87, and 88 present curves of accumulated snowmelt, accumulated evaporation, and accumulated runoff from the recorded hydrograph, including the recession contribution for the snowmelt seasons of 1948, 1949, and 1950, respectively. The computed evaporation loss appears to account for sizable fractions of the volumes of the snow-water equivalent involved in snowmelt and evaporation. The shape of the curves of the computed accumulated snowmelt approximate very closely the shape of the accumulated volumes from the recorded hydrograph. The critical change in the

Table 31—Evaporation from snow computed by Light's equation, 1950

St. Louis Creek, near Fraser, Colo.

Total inches for 24-hour period beginning at 0600 on date shown [1] (using basin constant K=1)

Date	Exclusive of periods having average temperature below 32° F	Including periods of average temperature below 32° F [2]
May 13 [3]	0. 109	0. 166
14 [3]	. 096	. 117
15	. 020	. 020
16 [3 4]	. 100	. 109
17 [4]	. 054	. 054
18 [3]	. 045	. 066
19	. 320	. 320
20 [3]	. 268	. 355
21 [3]	. 109	. 142
22	. 138	. 138
23	. 084	. 084
24	None	None
25 [3]	None	. 064
26 [3]	. 090	. 126
27	. 170	. 170
28 [3]	. 060	. 078
29	. 197	. 197
30	. 035	. 035
31	. 118	. 203
June 1 [3]	. 211	. 261
2 [3]	. 072	. 073
3 [3]	. 017	. 056
4 [3]	. 034	. 097
5	. 047	. 047
6	. 186	. 186
7 [3]	. 252	. 276
8 [3]	. 256	. 332
9	. 192	. 192
10	. 066	. 066
11	. 107	. 107
12	. 124	. 124
13	. 050	. 050
14	. 063	. 063
15	. 008	. 008
16	None	None
17	. 138	. 138
18	. 108	. 108
19	. 069	. 069
20	. 024	. 024
21	. 012	. 012
22	. 018	. 018
23	. 021	. 021
24	. 010	. 010
25	. 162	. 162
26	. 006	. 006
27	None	None
28	. 001	. 001
Total	4. 267	4. 951
Total through June 15	3. 698	4. 382

[1] Sum of evaporation for four 6-hour periods.
[2] Not corrected for change in vapor pressure of snow surface due to possible lowering of snow surface temperature when 6-hour average air temperature is below 32° F.
[3] Days in which there is at least one 6-hour period having average temperature below 32° F.
[4] Wind travel for these days estimated.

Table 32—Summary of evaporation [1] from snow computed by Light's equation, 1948, 1949, and 1950

St. Louis Creek, near Fraser, Colo.

Year	Inclusive dates [2]	Number of days	Computed evaporation (inches)	Average evaporation per day (inches)
1948	May 14–31	18	1.409	0.078
	June 1	1	.013	.013
	May 14–June 1	19	1.422	.075
1949	May 19–31	13	1.397	.107
	June 1–16	16	.503	.031
	May 19–June 16	29	1.900	.065
1950	May 13–31	19	2.013	.106
	June 1–15	15	1.685	.112
	May 13–June 15	34	3.698	.109
Total for Mays		50	4.819	0.096
Total for Junes		32	2.201	.069
Grand total		82	7.020	.086

[1] Exclusive of periods having average temperature below 32° F.
[2] Including day of largest volume contribution.

character of the hydrograph, following the day of largest volume contribution, is again clearly visible in the departure of Light's equation forecast volumes from the recorded hydrograph volumes.

It is interesting to note that in 1949 and 1950, during a portion of the snowmelt season, the loss of snow-water equivalent by evaporation was indicated as exceeding the contribution of snowmelt to runoff. There is no way of ascertaining whether or not this is true, since it should be kept in mind that the melt and evaporation losses to the snow pack are computed by Light's equation from data at only one instrument exposure—that is, at the windtower in the open, whereas the recorded runoff is from the St. Louis Creek gaging station, drainage basin area 32.8 square miles.

Figure 87, for the 1949 snowmelt season, shows the point which would have been attained on June 16 by Light's equation results had they been corrected by the basin constant of K=0.901 based upon 1948 data. Figure 88, for the 1950 snowmelt season, shows the point which would have been attained had Light's equation volumes been corrected through the use of the basin constant of K=0.947 which is the average of the basin constant of 0.901 for 1948, and 0.993 for the 1949 seasons. In both cases, the basin constants used were those based upon the period up to and including the day of largest volume.

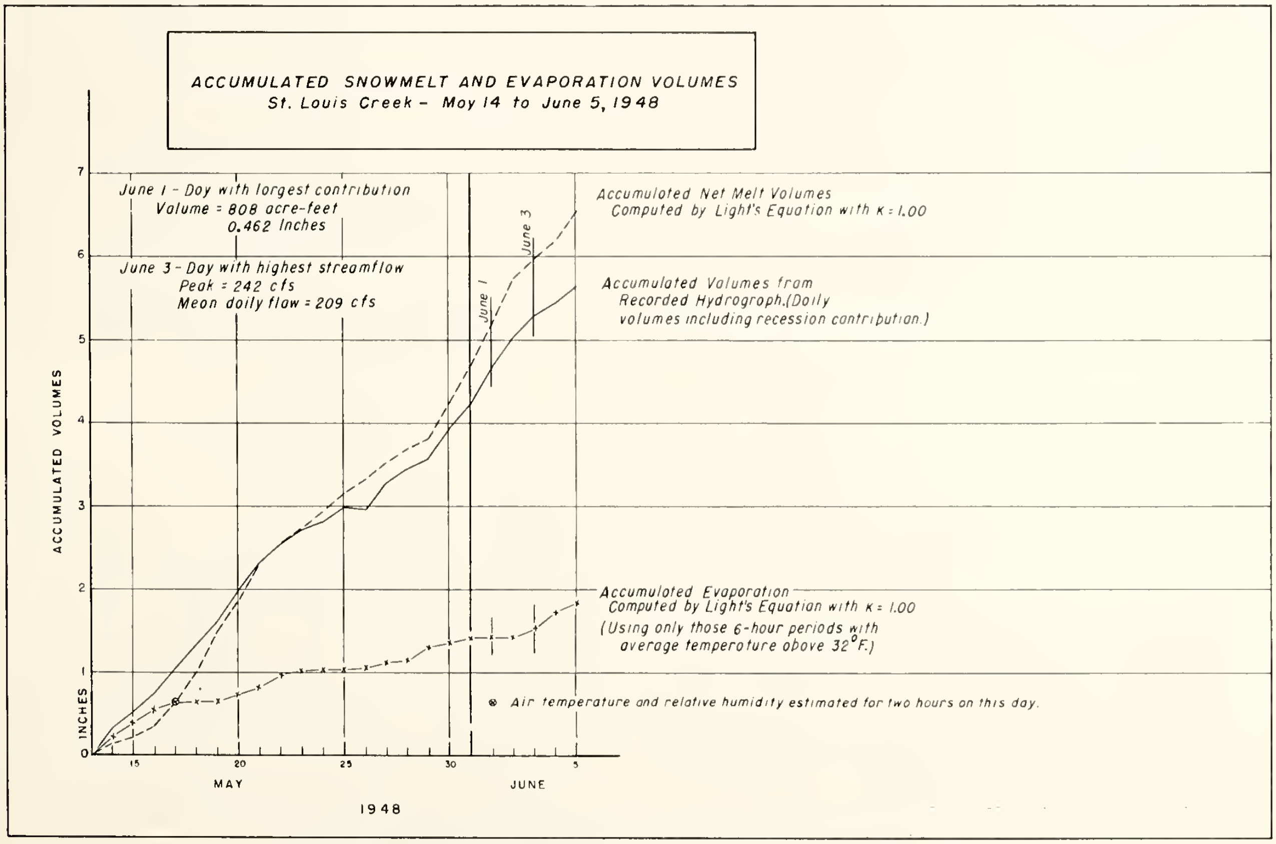

Figure 86. Accumulated snowmelt and evaporation, 1948.

A comparison of the melt, as computed by Light's equation without applying a basin constant and of the evaporation as computed by Light's equation, is given for the period through the day of largest volume contribution in summary form in table 33. Although the total melts for 50 days of the combined months of May and for 32 days of the combined months of June is approximately equal, the computed evaporation for the combined months of May is about twice that for the combined months of June. The grand total for 82 days for the 3 melt seasons which were analyzed by Light's equation is 17.919 inches of melt as compared with 7.020 inches of evaporation. Ratios of melt in relation to evaporation and the reciprocal of evaporation in relation to melt have been computed and are shown in table 33. The result of this computation of ratios is that, for the grand total of 82 days, for each 2.55 inches of melt computed by Light's equation, 1 inch of computed evaporation occurred, or, to express the results conversely, for each inch of computed melt there was 0.39 inch computed evaporation.

A review of figures 86, 87, and 88 indicates that Light's equation should be applied with caution to that period of the hydrograph following the day of largest volume contribution. Obviously, the reason for this is that although one can continue to substitute values of temperature, vapor pressure, and wind in Light's equation, there must be sufficient snow in storage on the drainage basin to absorb the heat and to produce melt. Thus, an intelligent application of Light's equation presupposes a knowledge of snow disappearance on the drainage basin if fantastic answers are to be obviated.

The surprisingly large indicated evaporation loss from the snow pack shown on figures 86, 87, 88, and table 34 centers attention on the importance of a critical study of evaporation losses not only from the snow pack but from the drainage basin upon which snowmelt yielding runoff is actively underway. The practical hydrologist, endeavoring to manage the water resources of a drainage basin with the utmost possible precision, is mainly interested in the total losses to the water yield of the drainage basin from combined evapo-

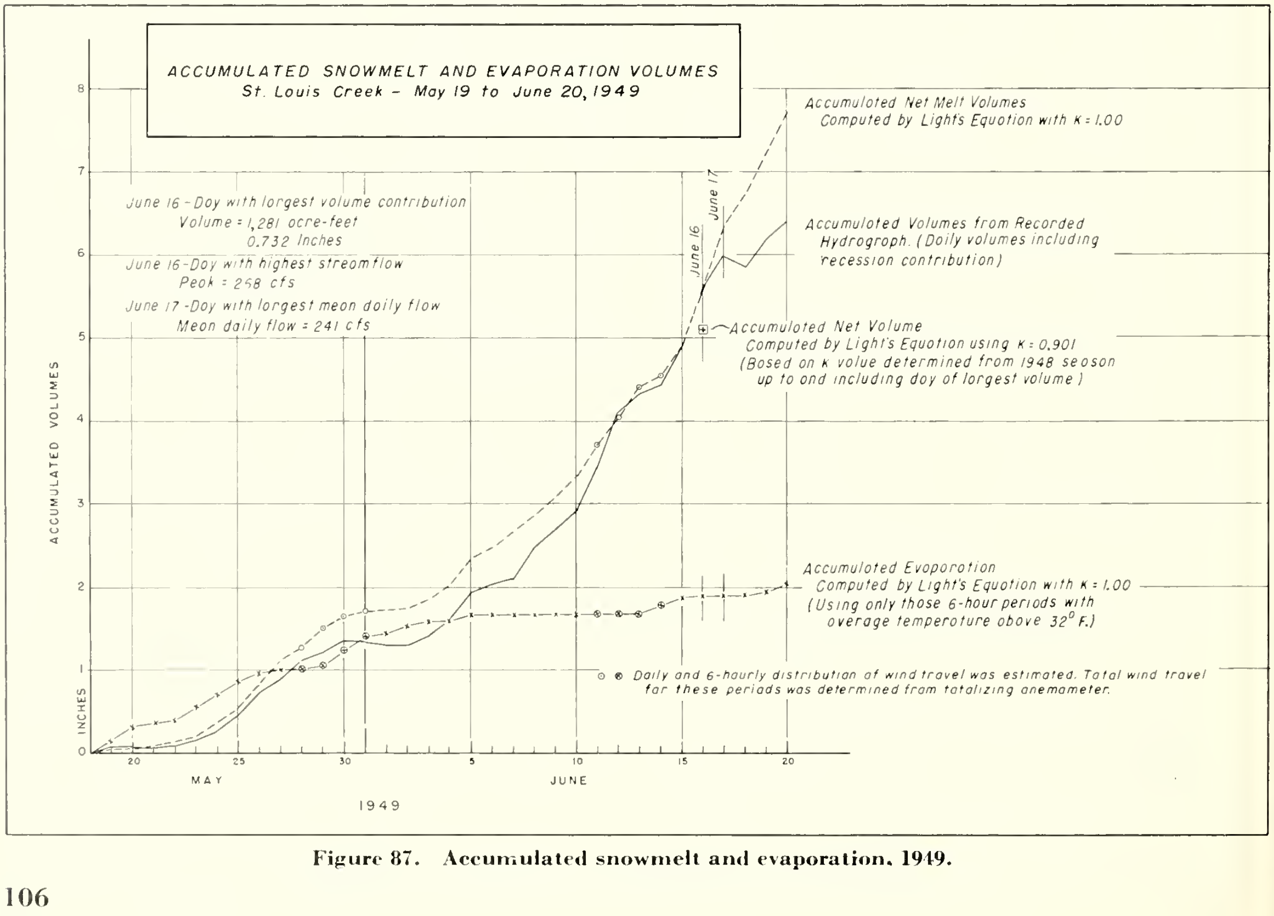

Figure 87. Accumulated snowmelt and evaporation, 1949.

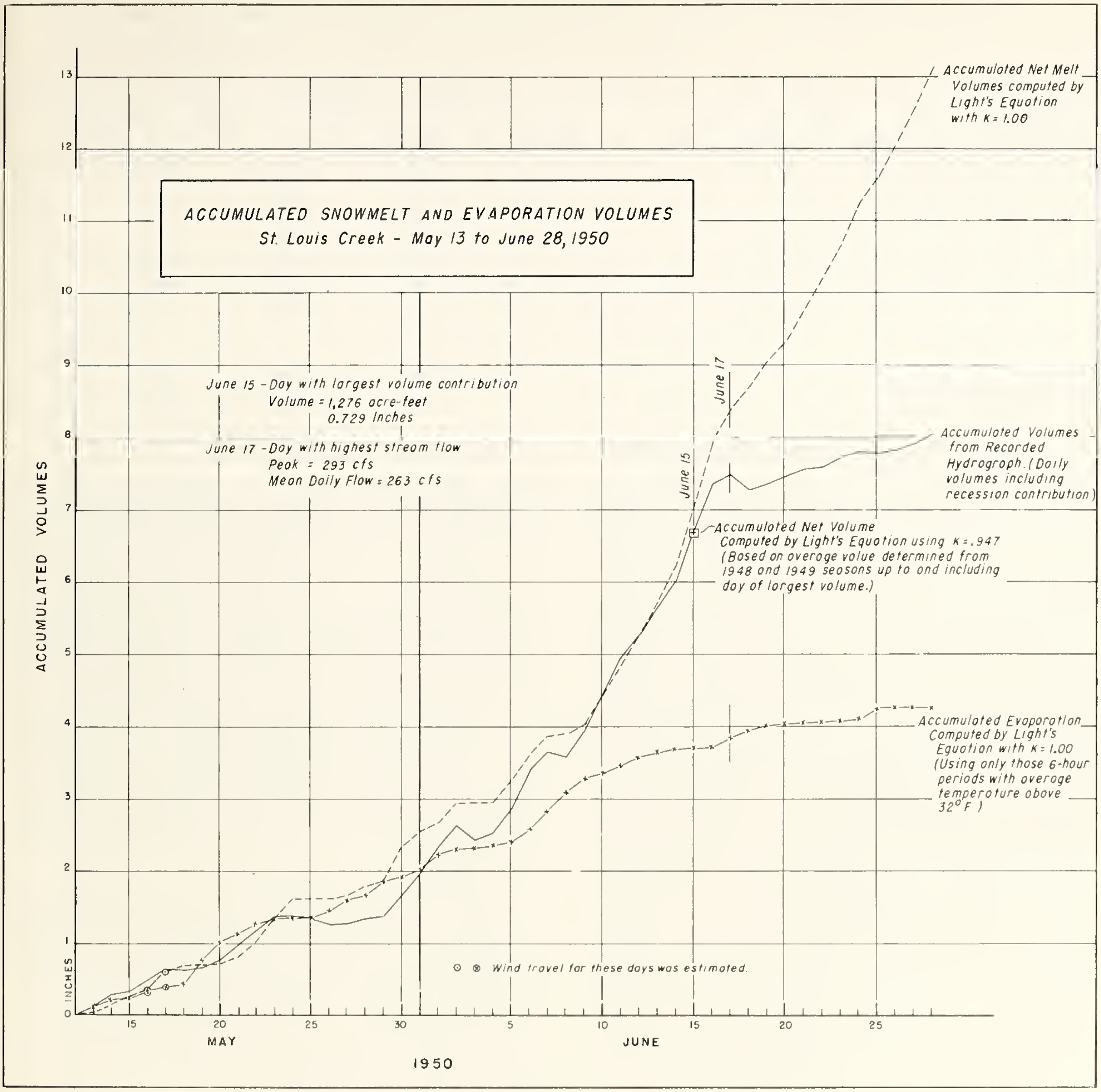

Figure 88. Accumulated snowmelt and evaporation, 1950.

ration and evapotranspiration. He does not need to know whether the loss occurs as evaporation from a snow crystal, whether it is evaporated from water which has been yielded by the melting of snow, or whether the loss is in the form of transpirational loss by vegetation. Although only a few of the numerous references available on a study of evaporation loss from snow as such have been reviewed in this paper, much remains to be done in introducing into seasonal water-yield forecast computations evapotranspirational loss of snowmelt to the water yield of the drainage basin as distinct from the loss of water directly from the snow crystals to the air.

As was brought out in the chapter on snow disappearance, a sizable fraction of the drainage basin may be bare of snow at the time of the peak rate of contribution to the snowmelt hydrograph, both including the recession flows and as expressed only in terms of daily peak rates of runoff above zero baseline of the hydrograph. There is a critical period in the annual spring flood snowmelt season when it is not possible to ascertain, either from snow surveys or from the current rate of

Table 33—Comparison of melt [1] and evaporation [2] as computed by Light's equation

St. Louis Creek, near Fraser, Colo.

Snowmelt season		Computed melt (inches)	Computed evaporation (inches)	Ratio: Melt / Evaporation	Ratio: Evaporation / Melt
Year	Inclusive dates [3]				
1948	May 14–31	4. 704	1. 409	3. 34	0. 30
	June 1	. 491	. 013	37. 77	. 03
	May 14–June 1	5. 195	1. 422	3. 65	. 27
1949	May 19–31	1. 701	1. 397	1. 22	. 82
	June 1–16	3. 967	. 503	7. 89	. 13
	May 19–June 16	5. 668	1. 900	2. 98	. 34
1950	May 13–31	2. 531	2. 013	1. 26	. 79
	June 1–15	4. 525	1. 685	2. 68	. 37
	May 13–June 15	7. 056	3. 698	1. 91	. 52
Total for Mays (50 days)		8. 936	4. 819	1. 85	. 54
Total for Junes (32 days)		8. 983	2. 201	4. 08	. 24
Grand total (82 days)		17. 919	7. 020	2. 55	. 39

[1] As computed by Light's equation without applying basin constant.
[2] Exclusive of periods having average temperature below 32° F.
[3] Including day of largest volume contribution.

discharge, exactly what is happening to the snow pack—whether it is going to appear in the form of water yield in a stream channel or whether significant fractions of the winter snow in storage are to be lost by evaporation and transpiration.

Since Light's equation offers distinct promise of making it possible to interpret the relative disposition of the snow pack between useful water yield and evapotranspirational loss, the Bureau of Reclamation in 1947 initiated the instrumentation of a series of hygrothermograph stations in the headwaters of the Colorado River drainage basin in Colorado for the purpose of differentiating, possibly in 5-day or weekly intervals, water-yielding conditions versus high evapotranspiration loss meteorological conditions as snowmelt progresses, so that an accounting could be kept of the direction in which the disappearing snow pack would be going—whether it would produce useful water yield or be lost to the atmosphere.

Although the results of Light's evaporation analysis in the Fraser Experimental Forest seem to be large as compared to the melt and when compared to the few figures available in the literature on snow evaporation, it should be kept in mind that Light's equation is an eddy-conductivity equation and that it would therefore tend to include a certain component of transpirational loss and evaporation loss from the free-water surfaces in addition to expressing the influence of vapor pressure differences between the air at the prevailing relative humidity and the vapor pressure of ice at the freezing point. This unlooked-for responsiveness of Light's equation is borne out by the observation that after several weeks' time at the windtower area in the open, the ground surface in the vicinity of the tower was bare of snow, although it remained saturated by the feeding of water from the melting snow pack further up slope, and that, in spite of the fact that there was no snow surface at the instrumental exposures, the result of the application of Light's equation to the data, nevertheless, is in close accord with the actual water yield as measured at the St. Louis Creek gaging station, as shown in the double-mass curves of figures 86, 87, and 88.

It is reasonable to expect, in the light of these results and of the snow disappearance study, that the above-discussed procedure for accounting for the disposal of the disappearing snow pack offers excellent promise of contributing significantly to the improvement of seasonal water-yield forecasting in drainage basins where vapor pressures are likely to be low during the snowmelt season.

This is illustrated by the experience in the headwaters of the Colorado-Big Thompson project drainage basin in Colorado when comparing the 1953 and 1954 snowmelt seasons. Although the average water equivalent of the snow pack, as measured by snow courses of the Federal Interstate Cooperative Snow Survey System, was about the same on April 1 of 1953 and 1954, the seasonal water yield in 1954 was considerably less due to the observed prevalence of temperatures about 20 degrees above normal and relative humidities far below normal during the course of the 1954 snowmelt season.

SECTION 11—SYNTHESIS OF THE SNOWMELT HYDROGRAPH

Both in project planning studies and in the operation of water resources utilization projects, there has been a need for the refinement of the techniques of computing seasonal water-yield forecasts, the estimates of momentary seasonal peak discharge, and the daily streamflows.

This part of the investigation was intended to develop and test a method of forecasting rates of runoff from snowmelt—in effect, a synthesis of the shape of the snowmelt hydrograph, based upon observed meteorological data as expressions of heat availability for the melting of snow. This approach, it will be noted, is different than the method of forecasting a seasonal peak rate of runoff based upon statistical relationships between the seasonal peak and the seasonal volumes of water yields. Techniques concerning that type of forecast are not the subject of this investigation.

Rate of runoff forecasts from snowmelt can be divided into two broad classes: the flood hydrology or design type of forecast, and the operational forecast. In both applications of snowmelt runoff forecasting, it is not necessary to resort to a graphical delineation of a complete standard recession curve for each day of snowmelt. Instead of using the curve, point values on the recession line below the daily peaks and troughs can be computed by the recession equation. It is not necessary to compute the day's contribution, including the recession flows, to the snowmelt hydrograph, since the prime interest in rate of runoff forecasting is the peaks and troughs of the forthcoming flows, and it is obvious that if these can be accurately forecast, the volume flows in the recessions, which are dependent on the daily peaks and troughs, will automatically be attained for whatever period is to be included in the rate of runoff forecast.

The relationships between the first day's volume, the height to peak, height to trough, and their interrelationships with the recession of the preceding day's contribution to the snowmelt hydrograph, as discussed in detail in section 8, and the correlations between the factors causing snowmelt and the water yields as discussed in section 9, suggested the technique for forecasting the shape of the snowmelt hydrograph.

The total volume of a day's contribution to the snowmelt hydrograph, the first day's volume, peak flow, and trough flow are presented in table 34 from the actual 1950 hydrograph and as synthesized by three methods: Method B, using Light's equation; Method C, using Equations 18 and 18–A from table 18; and Method D, using Equations 33 and 33–A from table 18.

A. Flood hydrology or design type of forecast

The data presented in table 34 are shown in graphic form in figure 89. In this type of forecast, meteorological data, adjusted by hydrometeorological techniques, are used as the basis for the synthesis of a flood or hydrograph of inflow in connection with considerations relative to the capacity or size of water control or conveyance structures. Once a point of takeoff on the hydrograph has been chosen, use is made of established relationships, such as simple correlation, multiple correlation equations, or Light's equation, to synthesize a hydrograph, with the results shown in table 34 and figure 89. No attempt is made in the flood hydrology type of forecast to correct the synthesized hydrograph to any observed hydrograph during the entire period under study.

In this type of forecast computation in which recession lines are not drawn and recession volumes are not computed, the hydrograph plotting point for the forecasting of peaks and troughs is found from the application of the appropriate recession coefficient to the previously derived point on the hydrograph. Thus, for flows above 30 c. f. s. in St. Louis Creek, when the daily recession coefficient $K=0.933$ is applicable, the recession coefficient for a 10-hour period becomes 0.972. For flows between 8 c. f. s. and 30 c. f. s., when the daily recession coefficient $K=0.981$, the recession coefficient for a 10-hour period becomes 0.992. For St. Louis Creek drainage basin, 32.8 square miles, the peak flows occurred at approximately 10 p. m.,

Table 31—Summary of volumes, peaks, and troughs as estimated from Light's equation, and equations 18, 18A, 33 and 33A for 1950

St. Louis Creek near Fraser, Colo.

Date	Measured from observed Hydrograph A*				Synthesized by Method B* using Light's equation				Synthesized by Method C* using Equations 18 and 18A				Synthesized by Method D* using Equations 33 and 33A			
	Total volume (acre-feet)	First day volume (acre-feet)	Peak flow [1] (C. f. s.)	Trough flow [2] (C. f. s.)	Total volume [3] (acre-feet)	First day volume [4] (acre-feet)	Peak flow [1 11] (C. f. s.)	Trough flow [2 8] (C. f. s.)	Total volume [5] (acre-feet)	First day volume [6] (acre-feet)	Peak flow [1 7] (C. f. s.)	Trough flow [2 8] (C. f. s.)	Total volume [9] (acre-feet)	First day volume [10] (acre-feet)	Peak flow [1 7] (C. f. s.)	Trough flow [2 8] (C. f. s.)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
May 13	186	9	30	24	41	9	32	23	20	12	34	23	148	14	36	27
14	305	12	35	28	150	18	40	28	151	28	47	27	279	32	54	35
15	44	7	35	28	214	24	49	35	99	18	44	30	152	15	48	38
16	305	18	42	34	154	**19	**51	**37	90	22	50	33	235	26	60	43
17	273	34	59	42	434	**42	**71	**49	**200	**34	**61	**37	340	40	76	51
18	−62	−2	44	37	146	18	64	51	−1	3	41	35	101	8	59	51
19	95	15	51	38	12	7	57	48	7	4	39	33	159	16	65	53
20	179	23	58	42	15	7	55	45	82	7	40	33	141	13	64	54
21	377	42	74	54	158	19	61	47	193	31	59	37	315	36	84	61
22	337	42	87	62	217	24	67	51	349	51	79	46	449	54	104	71
23	329	37	92	70	512	49	89	65	343	49	86	54	420	51	112	81
24	22	18	86	65	471	45	100	76	157	26	75	56	224	24	99	82
25	−34	1	68	59	0	6	81	71	−211	−36	29	45	−124	−22	65	73
26	−150	−8	55	49	0	6	76	66	**−199	**−17	**34	**36	−22	−9	66	67
27	18	5	55	47	58	11	75	64	59	4	40	36	116	10	76	67
28	93	16	61	47	242	26	84	67	178	14	48	39	159	16	80	67
29	87	10	54	47	119	16	80	67	78	14	52	39	152	15	80	68
30	490	44	79	62	759	70	120	87	345	53	83	48	424	51	109	77
31	535	50	102	77	352	35	114	93	273	39	79	53	340	40	109	83
June 1	637	62	126	94	214	24	111	94	355	47	91	61	460	−56	127	92
2	521	56	135	105	440	43	126	102	288	39	93	67	366	43	126	98
3	−366	−15	96	86	0	6	106	95	−266	−24	49	54	−98	19	83	88
4	176	16	96	86	31	8	102	90	−77	7	60	48	116	10	96	86
5	574	54	126	100	493	47	126	100	289	53	91	54	424	51	127	94
6	976	93	172	126	601	56	142	113	560	72	111	69	663	83	159	109
7	411	67	191	131	440	43	144	119	387	43	103	76	442	53	151	116
8	−114	5	138	117	35	9	126	113	61	7	83	73	159	16	128	114
9	611	48	162	131	211	24	130	112	180	29	97	74	330	38	143	117
10	931	104	218	152	656	61	157	126	472	74	133	85	605	75	175	128
11	867	114	239	170	678	63	172	140	**539	**77	**146	**96	**674	**85	**194	**142
12	543	96	251	175	688	64	186	153	528	74	155	107	638	80	203	153
13	698	105	260	185	775	71	204	168	549	77	167	118	652	82	215	163
14	609	106	266	191	821	75	222	183	543	77	177	127	667	84	227	174
15	1,276	113	263	221	1,415	124	274	217	630	93	199	139	746	94	246	186
16	1,085	97	284	242	1,495	132	311	250	607	103	219	149	739	93	257	198
17	217	64	296	230	708	65	295	257	589	82	212	158	707	89	264	207
18	−391	27	269	200	513	49	289	256	451	61	204	162	580	72	260	212
19	155	34	239	191	587	55	293	258	468	63	209	167	576	72	265	216
20	208	22	215	185	435	42	286	255	296	54	207	165	456	55	256	217
21	164	30	209	178	748	69	302	262	419	60	210	167	496	61	261	218

22	68	16	191	168	706	65	306	268	402	53	207	169	500	61	263	220
23	204	35	191	162	767	70	315	275	509	81	231	175	696	88	285	227
24	133	41	191	155	958	86	334	287	568	80	235	181	703	89	293	235
25	−31	26	182	142	571	54	322	287	510	74	237	186	623	78	292	239

*Please refer to legend on figure 89.

**Computed from estimated values of one or more of the weather elements.

[1] Peak flow occurring at approximately 10 p.m. on date listed.

[2] Trough flow occurring at approximately noon of the next day.

[3] Total volume computed from Light's equation using basin coefficient derived from 1948 and 1949 data using days before and including day of peak volume only: K=0.947.

[4] First day volume computed from figure 72 using days before and including day of peak volume only.

[5] Total volume computed from Equation 18 (table 18) which was derived from 1948 and 1949 data.

[6] First day volume computed from Equation 18A (table 18) which was derived from 1948 and 1949 data.

[7] Peak flow computed from figure 74.

[8] Trough flow computed from figure 76.

[9] Total volume computed from Equation 33 (table 18) which was derived from 1948 and 1949 data.

[10] First day volume computed from Equation 33A (table 18) which was derived from 1948 and 1949 data.

[11] Peak flow computed from figure 73 using line for days before and including day of peak volume only.

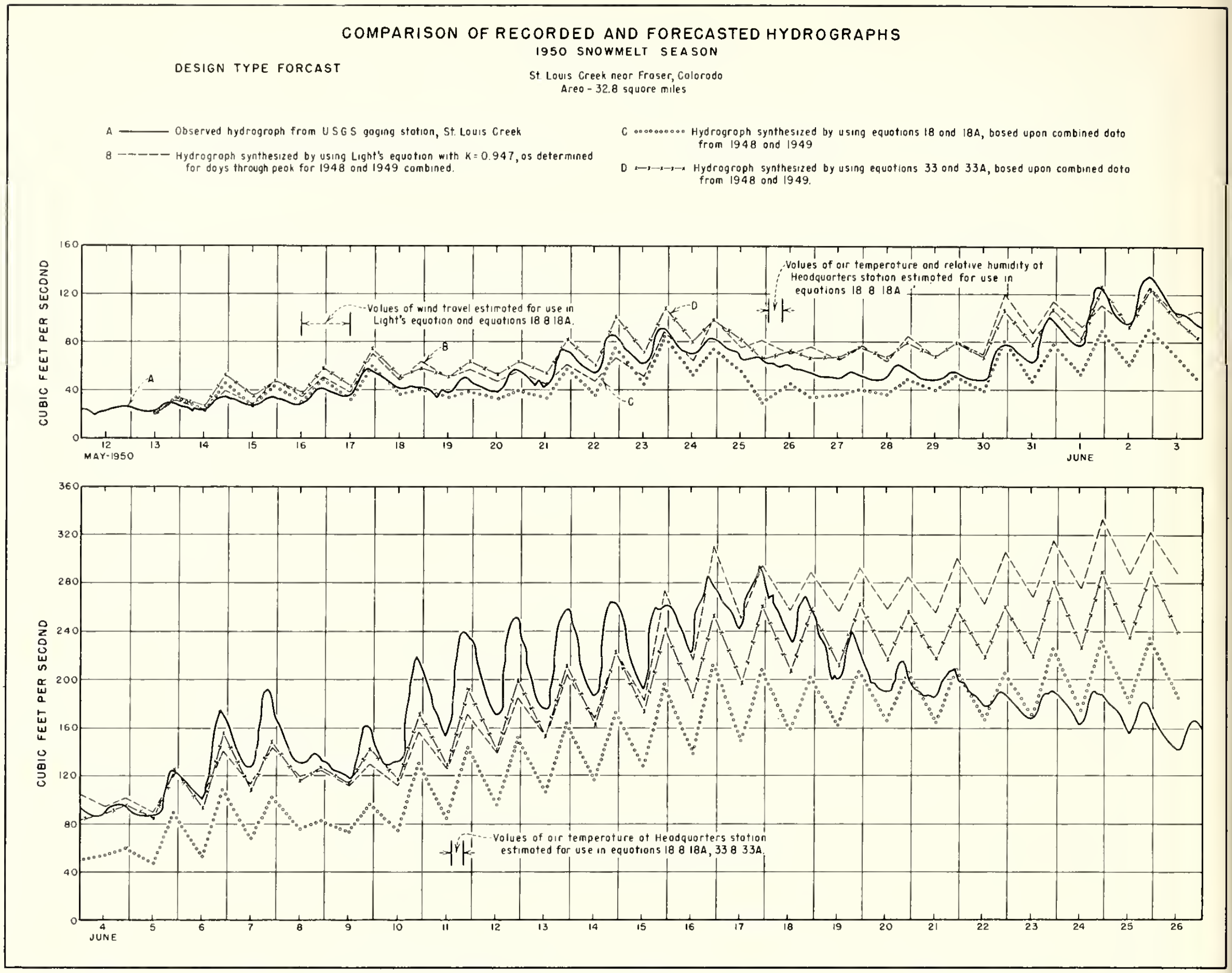

Figure 89. Comparison of recorded and seasonally forecasted hydrograph for St. Louis Creek near Fraser, 1950.

and the trough flow occurred at approximately noon of the following day.

In figure 89, the solid-line hydrograph is the observed flow at the St. Louis Creek gaging station near Fraser, Colo. The dashed line is the design type of forecasted hydrograph, as synthesized by using Light's equation with a K=0.947, as determined for days before and through the peaks for 1948 and 1949.

The open-circle hydrograph was synthesized by using Equations 18 and 18–A, based upon combined 1948–49 correlation analyses. The barbwire-symbol hydrograph was synthesized by using Equations 33 and 33–A, simple correlations, with degree-days above 32° F at the headquarters, based upon combined data for 1948–49. A perusal of figure 89 discloses that the best fit of forecast and actual design-type hydrographs was attained about the peak of the seasonal flow by Light's equation and Equations 33 and 33–A, with not much difference evident between them.

The multiple-correlation Equations 18 and 18–A did not yield nearly as good a synthesized hydrograph as did the other two. The three synthesized hydrographs were continued past the date of peak snowmelt contribution, June 17 through June 25, to illustrate the danger of synthesizing snowmelt runoff based upon heat units alone without a knowledge of whether or not there is sufficient snow remaining on a drainage basin to be available for snowmelt. All three hydrographs mount far above the recorded hydrograph simply because the equations continue to yield results indicating a melting of snow which are not realistic, since the snow pack has by that time been reduced to a continuously shrinking area, having progressively less and less significance in terms of streamflow.

B. Operational type of forecast

An operational type of day-by-day forecast of peak and trough flows, rather than of a continuous hydrograph, was computed for 1950, using relationships derived from the data for the combined 1948–49 snowmelt seasons. The heights to peaks and to troughs for each day were derived as described for the data in table 34. However, in this day-by-day forecast, the start of the forecasted hydrograph for a day was taken to be the observed trough of the preceding day, on the assumption that the preceding day's trough discharge would be known at the time the forecast was being made. In this operational type of forecast, the more commonly available single indexes, such as degree-days and maximum temperatures, were used.

This operational-type forecast is shown in figure 90. Line A is the actual hydrograph of the 1950 snowmelt season. Line E designates the daily peaks and troughs forecast by using degree-days above 32° F as computed from hourly temperatures from a thermograph trace. Line F shows the daily peaks and troughs forecast by using the

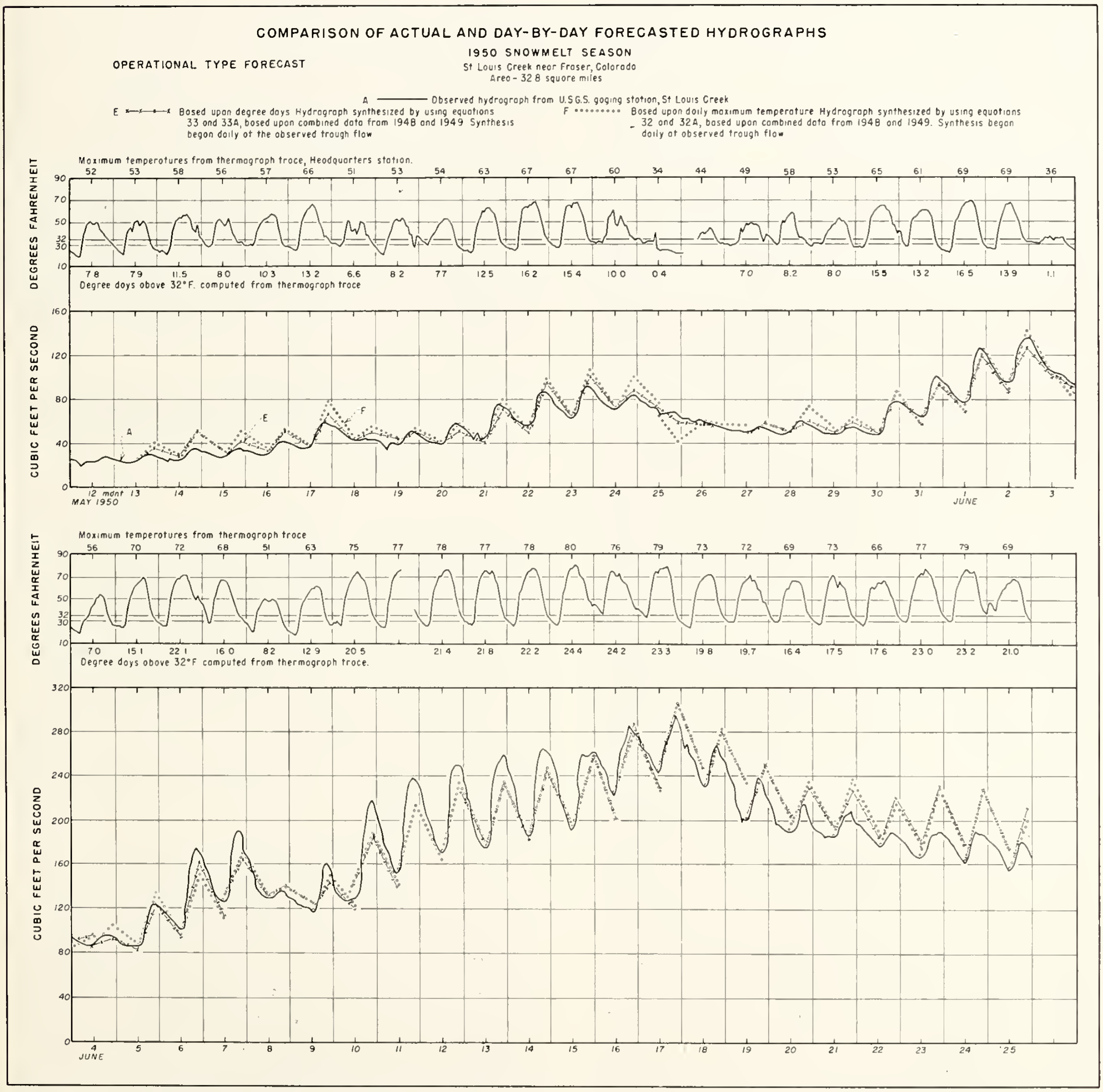

Figure 90. Comparison of recorded and day-by-day forecasted hydrograph for St. Louis Creek near Fraser, 1950.

daily maximum temperature as read from the thermograph chart. The use of the daily maximum temperature makes it possible to forecast the peak rate of runoff which occurs at St. Louis Creek about 10 p. m. on the day of the observation, and the trough rate of runoff which occurs about noon on the following day. Acquaintanceship with the geometric shape of the daily rise and fall of the snowmelt hydrograph makes it possible for the practicing hydrologist to sketch an assumed shape of the day's fluctuation of streamflow from the known trough to the forecasted peak and to the forecasted trough, thus permitting a computation of not only the rates of discharge but also of the total volume of flow to be expected to go past the gaging station during the next 24-hour period under forecast.

In addition to the actual and forecasted daily peaks and troughs, figure 90 contains maximum temperatures from the thermograph trace as taken at the headquarters station, and degree-days above 32° F computed from the thermograph trace, together with a charting of the hourly values of temperature as recorded at the headquarters station in the Fraser Experimental Forest. The significance of the recession concept as applied to the analysis and synthesis of the snowmelt hydrograph is illustrated by comparing, on figure 90, the degree-days above 32° F from the thermograph trace and the recorded discharges for June 6, on which there were 22.1 degree-days, and the peak rate of discharge was 172 c. f. s., with those of June 17, on which there were 23.3 degree-days, whereas the peak rate of discharge was 296 c. f. s.

In a parallel study for the 1949 snowmelt season, based upon data derived from the 1948 season only, which is reported in Reference 85, it was observed that the greatest discrepancy between the actual and forecasted operational volume occurred on days when air temperatures remained throughout above 32° F at the headquarters station, when single index factors, such as daily maximum temperature or degree-days above 32 alone, were used. Under such conditions, multiple-correlation equations and Light's equation gave better results. In an actual operational type of forecast, some cognizance might be given to the influence of melting conditions throughout the night. Such conditions are not common in the Rocky Mountains in Colorado as temperatures are usually below freezing practically every night during the course of the snowmelt season, and this problem in interpretation of heat units in relation to snowmelt was not an important one at the Fraser Experimental Forest.

Evaluation of the accuracy of rate of runoff forecasting depends, to some extent, upon the purpose for which the forecast is performed and the prevailing operation at the time the forecast is made. Although considerable differences in the numerical value of the discharge, as expressed in cubic feet per second, might exist, in case of diversions or flood control operations, the critical figure is that of the gage height of the stream rather than the rate of discharge, since the channel configuration at the point of measurement becomes important in determining the depth of flow or gage height, as expressed in rating tables. Thus, 265 c. f. s. corresponds to a gage height of 2.30 feet at the St. Louis Creek gaging station; and 274 c. f. s. corresponds to a gage height of 2.33 feet at the gaging station. The difference, 0.03 of a foot, amounts to about 0.3 of an inch. Similarly, 216 c. f. s. corresponds to a gage height of 2.14 feet, while 204 c. f. s. corresponds to a gage height of 2.10 feet, and the difference, 0.04 foot, amounts to about half an inch.

C. Forecasting day-by-day snowmelt runoff, Blue River above Green Mountain Reservoir, Colorado

Green Mountain Reservoir, a unit of the Bureau of Reclamation's Colorado-Big Thompson project, is located on the Blue River 14 miles southeast of Kremmling, Colo. The reservoir has a total capacity of 154,600 acre-feet and an active capacity of 146,900 acre-feet, whereas the average inflow of the Blue River to Green Mountain Reservoir for the four months, April through July, amounts to 306,200 acre-feet as based upon the period 1900–54. The drainage basin contributing to Green Mountain Reservoir has an area of 514 square miles, or almost 16 times the size of the St. Louis Creek drainage basin.

Taking into account the average April-through-July inflow and the active capacity of the reservoir, it is evident that even during flood seasons of relatively low water yield, Green Mountain Reservoir would fill and spill. A day-by-day forecast of snowmelt runoff was estimated to be of value in assisting on decisions on drawdown for power generation, so that inflows beyond storage capacity might be utilized for hydroelectric energy genera-

tion without spill and with assurance of maintaining the reservoir storage at capacity as long as desired. The peak of the power demand is at about 6 p.m., and during years of below-normal outlook for inflow, the powerplant has been operated to meet peak demand only, in which case rate of runoff forecasting would be of value. During years of abundant water supply, such as 1951 and 1952, the Green Mountain Powerplant was operated steadily at hydroelectric plant capacity for the period April to June, and rate of runoff forecasting would have been of minor assistance prior to the first of July during those years.

Snowmelt runoff in the Blue River drainage basin exhibits wide variation between the peaks and the troughs of the days' contribution to runoff. An instance of the magnitude of the difference between peak and trough, amounting to 1,584 c.f.s., occurred between the peak of 5,002 c.f.s. and the trough of 3,418 c.f.s. on the melt runoff which occurred from heat of June 10, 1952. This trough was followed by a peak of 4,440 c.f.s. from the melt of June 11, 1952. Because of variations of such magnitude, a method of day-by-day forecasting of snowmelt runoff offered promise of considerable value as an aid in reservoir operations during the relatively frequent times during the snowmelt season when Green Mountain Reservoir is approaching complete filling, expecially in the vicinity of the peak of the seasonal snowmelt runoff.

In view of the success attained in forecasting rates of runoff for St. Louis Creek, as indicated in figures 89 and 90, a method of forecasting, based upon the concept demonstrated for St. Louis Creek, was developed for Green Mountain Reservoir [44].

As there was no thermograph record of air temperatures available within the Blue River drainage basin, the daily maximum and minimum observations from the cooperative weather station at Green Mountain Village, located immediately downstream of the dam, were used. Since peak rates of discharge occured in 1951–52 of a magnitude considerably greater than any previously recorded, these two years were used in the derivation of a standard recession curve and of the recession coefficient in order to have available for use in 1953 and subsequent years a curve based upon data encompassing the higher rates of discharge.

In developing this forecast, no attempt was made to segregate major components of runoff from snowmelt into surface, subsurface, or groundwater flows. The aim was to derive a recession curve which would be useful in making an operational forecast. The Blue River above Green Mountain Reservoir was found to possess a variable rate of recession above 1,400 c.f.s., and for operational purposes, reasons why the recession should vary were not pertinent to the operators as long as the recession curve was a true expression of the characteristics of the drainage basin as they influenced the release of streamflow from snowmelt. Both the constant and the variable recession rates for the Blue River above Green Mountain Reservoir are shown in the form of a curve, figure 91.

To facilitate the preparation of a forecast, the recession curve (figure 91) was prepared in the form of a transparent plastic template with a cutaway edge for flows between 900 and 5,200 c. f. s., and a row of holes drilled in the template for flows between 935 and 550 c. f. s. The recession in this drainage basin for flows between 1,400 and 100 c. f. s. was found to possess the recession coefficient $K_r=0.958$ for daily discharges. The computation of contributions to runoff, when a discharge drops below 100 c. f. s., was not recommended for two reasons: Records of discharge at such low levels in the wintertime are relatively inaccurate due to ice effect at the gaging station, and the residuals of the individual day's snowmelt contributions become very small in a drainage basin of this size, 514 square miles in area.

For this operational forecast, a rising hydrograph was considered one in which the flow at the trough of the next day was to be greater than that of the current day, the relative size of the days' peaks notwithstanding. A falling or receding hydrograph is one in which the flow at the trough of the next day was lower than that of the current day, the relative size of the days' peaks notwithstanding. This classification was based upon the observation that the position of a trough is a much more conservative characteristic of the snowmelt hydrograph than is the peak rate of discharge of a day's contribution to runoff. The daily peak may be affected greatly by the pattern of distribution of available heat and by the hydraulics of the tributary channels, among other factors, whereas the trough reflects in a more integrated manner the degree of saturation of the drainage basin from a given day's snowmelt contribution to runoff.

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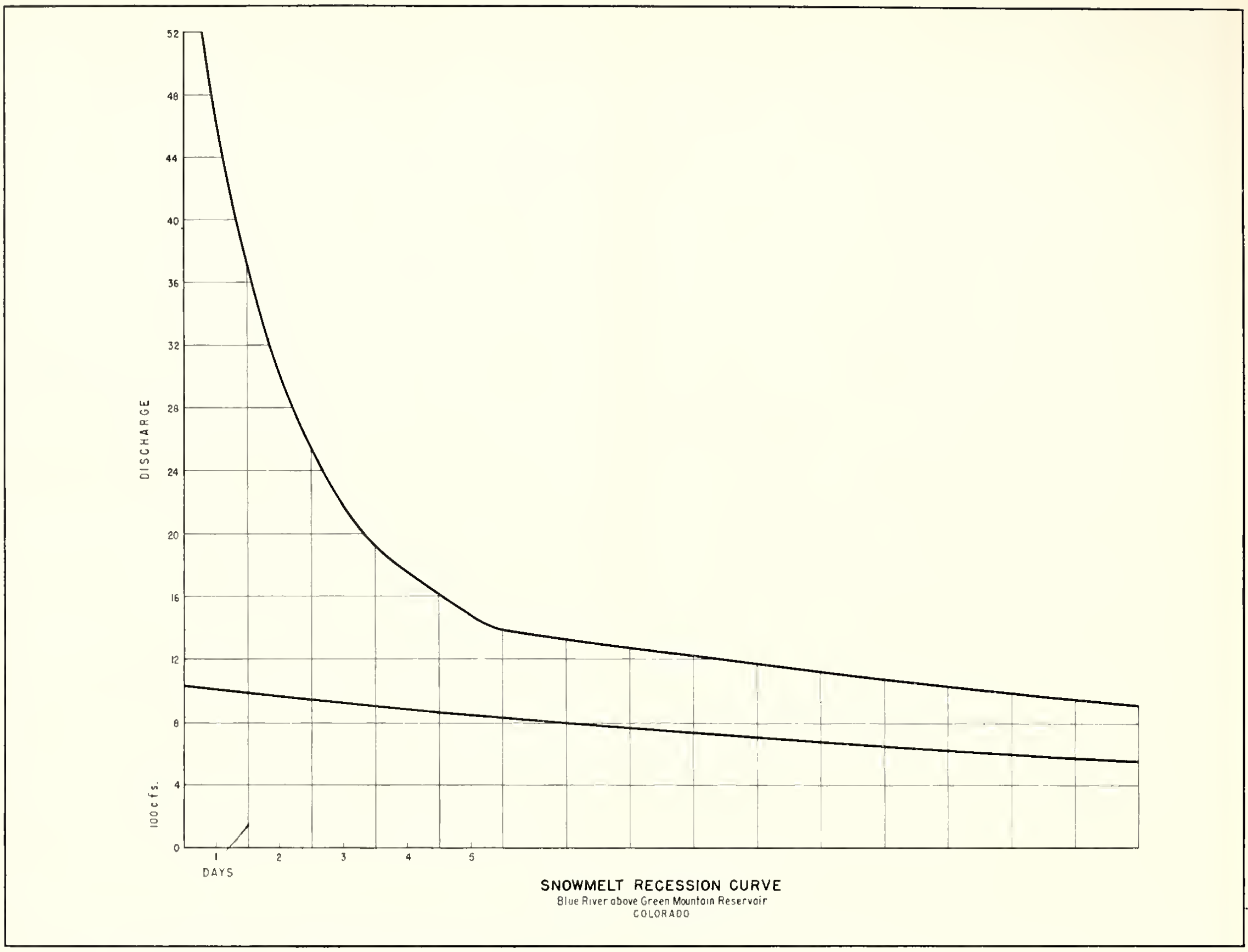

Figure 91. Snowmelt recession curve for Blue River above Green Mountain Reservoir.

It was noted that the shape of the first day's runoff, the hydrograph between successive troughs, is roughly a parabola on the rising hydrograph, whereas it approximates the shape of a cone on the receding hydrograph. The temperature function used in this operational forecast made use of both maximum and minimum temperatures, since the only source of temperature data was below the contributing drainage basin in elevation. The temperature function used consisted of the sum of the current day's maximum and of one-half of the value of the preceding day's maximum plus the current morning's minimum temperatures. A temperature function which included the minimum was selected after a comparative study, since it appeared to reflect more accurately the length of time when melting of snow might have taken place at the higher elevations under such a regimen of diurnal temperature progression than did the daily maximum temperature alone, as observed at Green Mountain Village in a very narrow valley below the dam.

A cumulative temperature index, which is described by Hildebrand and Bottorf [53], offered promise in connection with the operational forecasting problem and was used.

The cumulative temperature is looked upon as an integrating index of a process which has been observed in the field. As the so-called "snow-line" recedes so that the snow-covered area is being progressively reduced, the contribution of runoff waters released from snowmelt must travel progressively increasing distances to major stream channels. In the meanwhile, the advance of spring brings increasing temperatures at the lower elevations. These increasing temperatures step up the evapotranspirational loss, not only from the retained soil moisture but also from the subsurface waters in transit from the actively melting snow.

Table 35—Summary of correlations for Blue River above Green Mountain Reservoir, 1951 and 1952

Equation No.	Dependent variable	X_2	X_3	X_4	X_5	a	$\bar{R}$	$\bar{S}$
Days through the peak, N=83:								
1	$X_{1.34}$		0. 2888	33. 9475		−3798. 00	0. 848	333. 96
3	$X_{1.23}$	49. 9317	. 3188			−3215. 90	. 830	350. 30
5	$X_{1.25}$	50. 0360			0. 1808	−3218. 70	. 830	350. 60
7	$X_{1.45}$			34. 0089	. 1637	−3801. 40	. 847	334. 20
Days past the peak, N=31:								
2	$X_{1.34}$		−1. 0586	27. 2913		1095. 00	. 835	373. 70
4	$X_{1.23}$	39. 2579	−1. 0386			1686. 00	. 831	377. 96
6	$X_{1.25}$	38. 5787			−. 5878	1701. 00	. 826	383. 24
8	$X_{1.45}$			26. 7936	−. 5990	1124. 00	. 830	379. 22

List of variables used in correlation analysis of daily snowmelt

Identification	Description of variable	Units
X_1	First day's volume	Acre-feet.
X_2	Current day's maximum temperature	°F.
X_3	Cumulative from May 1st current day's maximum temperature	°F.
X_4	Temperature function*	°F.
X_5	Cumulative from May 1st temperature function	°F.

*Temperature function=[½ (preceding day's maximum plus current morning's minimum)] plus [current day's maximum].

Thus, whereas a day's contribution to snowmelt runoff depends upon the heat available at the snow field on that day, the rising toll of evapotranspirational loss is related to accumulative heat, operating not only over the snow field but also over the drainage basin as a whole.

As was the case at St. Louis Creek, a critical point in a snowmelt hydrograph for the Blue River above Green Mountain Reservoir was the peak of the snowmelt contribution to runoff. Therefore, multiple-correlation analyses were performed separately for the periods through the peak day and for the recession of the seasonal snowmelt hydrograph. For 1951, the rise through the peak day was from May 6 through June 20, and the recession was from June 21 through June 29. For 1952, the rise through the peak day was May 1 through June 7, and the recession June 8 through June 29. In the multiple-correlation analyses, the variables were defined as follows:

X_1 was the first day's volume (acre-feet).

X_2 is the day's maximum temperature (degrees Fahrenheit).

X_3 was the current maximum temperature in degrees Fahrenheit cumulative from May 1.

X_4 was the temperature function (degrees Fahrenheit).

X_5 is cumulative from May 1 temperature function in degrees Fahrenheit.

The results of this series of correlation analyses are given in table 35.

In order to ascertain whether or not the factors as used in this series of forecast equations were significant, the standard error of the "b" coefficients was computed in the manner outlined by Ford [37], in which the recommendation is made that, for a factor to be significant, the standard error of the "b" coefficient should be less than half of the "b." This analysis yielded the ratios shown in table 36.

In the table, it is to be noted that the ratio of standard error of the "b" coefficient to the "b" is, in every instance, less than half the "b", indicating that the factors used in this series of multiple-

Table 36—Summary of standard error of "b" coefficients in multiple-correlation equations for Blue River above Green Mountain Reservoir

Equation No.	Variable and coefficient	Standard error of "b" coefficient	Ratio
1	$0.29X_3$	0. 05	0. 163
1	$33.95X_4$	3. 28	. 097
2	$-1.06X_3$	. 17	. 156
2	$27.29X_4$	11. 14	. 408
3	$49.93X_2$	5. 24	. 105
3	$.32X_3$	. 05	. 152
4	$39.26X_2$	17. 15	. 437
4	$-1.04X_3$	. 17	. 166

correlation equations are significant. Equations 1 and 3 for the days through the peak are based upon 83 days. Equations 2 and 4, for the days past the peak are based on 31 days. A total of 114 days of snowmelt contribution to runoff was used in this computation of the forecast. It is interesting to note that the cumulative temperature index, X_3, in the equations for the days past the peak exhibits a negative sign, thus exerting a depleting influence upon water yield of Equations 2 and 4 which are for the days past the peak. This result substantiates the line of reasoning in support of the use of a cumulative temperature expression to represent, in the forecast procedures, the depletion of the snow cover concurrent with the increase in temperature which has been shown to change the characteristics of the hydrograph of the snowmelt runoff at the time of the seasonal peak of volume contribution.

Relationship between the height to peak above the preceding day's recession and the first day's volume for the Blue River above Green Mountain Reservoir is given in figure 92. The height to trough, in relation to the first day's volume, is given in figure 93. The relationship shown of figures 92 and 93 are based upon 114 points each. Correlation coefficients of an exceptionally high order, 0.991 to 0.978, respectively, were attained for this 514-square-mile drainage basin.

The results of the application of the forecast procedures to 1953 are given in table 37, in which it is noted that the average percent departure of the forecast from actual total daily inflow for the period June 1 through June 29, 1953, was within 12 percent. This forecast is illustrated graphically in figure 94.

D. St. Louis Creek snowmelt runoff forecasted from Fraser, Colo., maximum temperatures

In view of the success attained in forecasting the Blue River above Green Mountain Reservoir through the introduction of a cumulative tem-

Table 37—Comparison between actual and estimated inflow volumes for Blue River above Green Mountain Reservoir, 1953

1	2	3	4	5	6	7	8	9	10	11	12
Melt of June 1953	Residual flow	Actual net first day volume	Actual total inflow for day	Estimated net first day volume (X_2X_3 EQ.)	Estimated total inflow for day (X_2X_3 EQ.)	Departure of (6) from (4) (X_2X_3 EQ.)	Percent departure (X_2X_3 EQ.)	Estimated net first day volume (X_3X_4 EQ.)	Estimated total inflow for day (X_3X_4 EQ.)	Departure of (10) from (4) (X_3X_4 EQ.)	Percent departure (X_3X_4 EQ.)
1	3, 380	904	4, 284	1, 247	4, 627	343	8. 0	1, 582	4, 962	678	15. 8
2	3, 636	1, 079	4, 715	1, 623	5, 259	544	11. 5	1, 657	5, 293	578	12. 3
3	3, 735	785	4, 520	846	4, 581	61	1. 3	1, 032	4, 767	247	5. 5
4	3, 576	381	3, 957	1, 420	4, 996	1, 039	26. 3	1, 157	4, 733	776	19. 6
5	3, 150	341	3, 491	692	3, 842	351	10. 1	955	4, 105	614	17. 6
6	2, 926	214	3, 140	813	3, 739	599	19. 1	770	3, 696	556	17. 7
7	2, 781	41	2, 822	1, 236	4, 017	1, 195	42. 3	1, 114	3, 895	1, 073	38. 0
8	2, 503	754	3, 257	1, 510	4, 013	756	23. 2	1, 425	3, 928	671	20. 6
9	2, 872	1, 365	4, 237	1, 737	4, 609	372	8. 8	1, 636	4, 508	271	6. 4
10	3, 491	1, 515	5, 006	1, 763	5, 254	248	5. 0	1, 813	5, 304	298	6. 0
11	4, 052	1, 674	5, 726	1, 739	5, 791	65	1. 1	1, 853	5, 905	179	3. 1
12	4, 661	2, 102	6, 763	1, 816	6, 477	−286	−4. 2	1, 928	6, 589	−174	−2. 6
13	5, 054	2, 388	7, 442	1, 892	6, 946	−496	−6. 7	2, 105	7, 159	−283	−3. 8
14	5, 098	809	5, 907	1, 869	6, 967	1, 060	17. 9	2, 095	7, 193	1, 286	21. 8
15	4, 350	912	5, 262	1, 680	6, 030	768	14. 6	1, 736	6, 086	824	15. 7
16	4, 040	1, 301	5, 341	1, 788	5, 828	487	9. 1	1, 782	5, 822	481	9. 0
17	4, 241	1, 071	5, 312	1, 508	5, 749	437	8. 2	1, 670	5, 911	599	11. 3
18	4, 284	897	5, 181	1, 502	5, 786	605	11. 7	1, 597	5, 881	700	13. 5
19	4, 959	1, 166	6, 125	958	5, 917	−208	−3. 4	1, 154	6, 113	−12	−. 2
20	4, 122	452	4, 574	1, 000	5, 122	548	12. 0	941	5, 063	489	10. 7
21	3, 596	436	4, 032	1, 039	4, 635	603	15. 0	928	4, 524	492	12. 2
22	3, 412	468	3, 880	1, 113	4, 525	645	16. 6	980	4, 392	512	13. 2
23	3, 253	532	3, 785	1, 106	4, 359	574	15. 2	1, 043	4, 296	511	13. 5
24	3, 128	381	3, 509	1, 021	4, 149	640	18. 2	998	4, 126	617	17. 6
25	2, 936	190	3, 126	553	3, 489	363	11. 6	567	3, 503	377	12. 1
26	2, 743	182	2, 925	708	3, 451	526	18. 0	580	3, 323	398	13. 6
27	2, 628	151	2, 779	627	3, 255	476	17. 1	633	3, 261	482	17. 3
28	2, 525	254	2, 779	737	3, 262	483	17. 4	668	3, 193	414	14. 9
29	2, 505	151	2, 656	574	3, 079	423	15. 9	610	3, 115	459	17. 3
Totals			126, 533		139, 754	*15, 201			140, 646	*15, 051	
Averages							12. 0				11. 9

*Added without regard to sign.

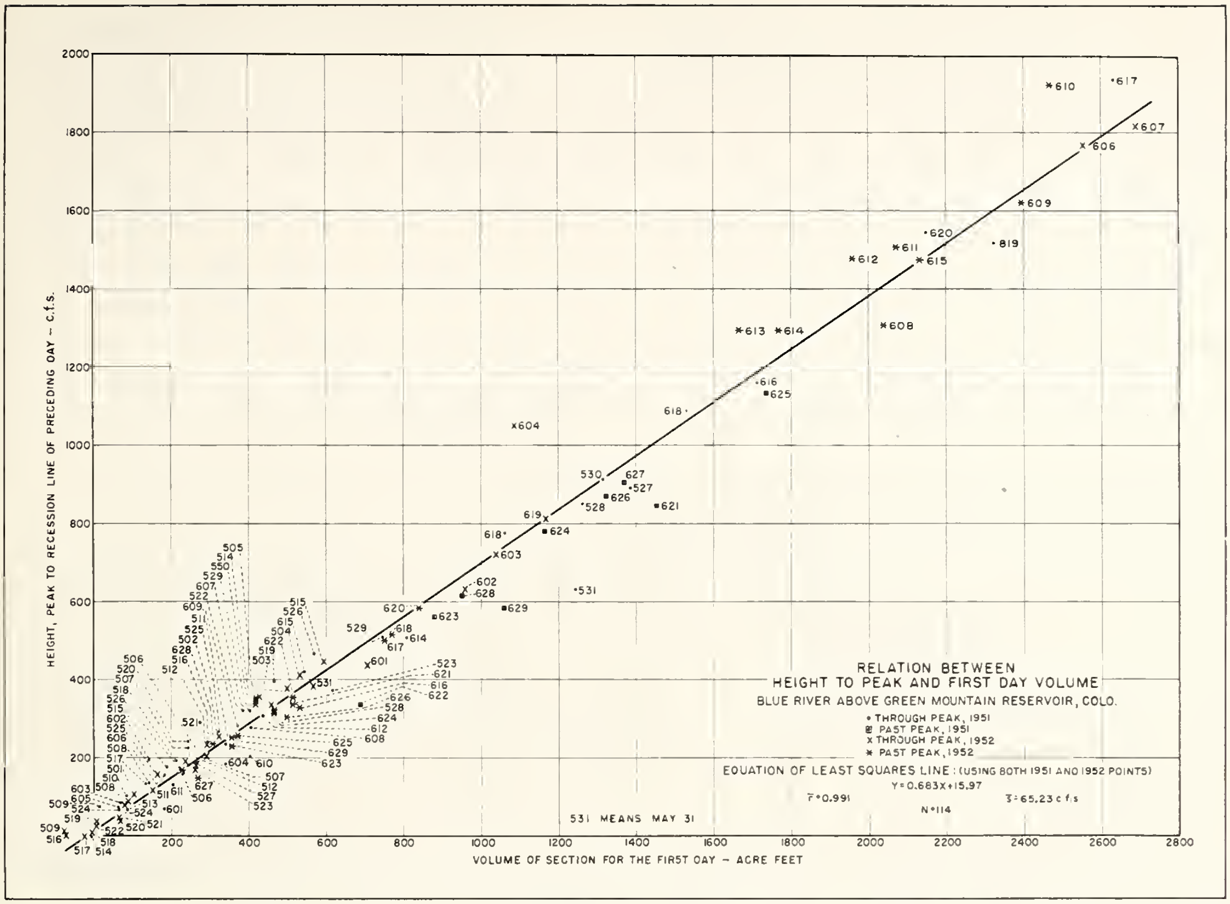

Figure 92. Relation between height to peak and first day volume, Blue River above Green Mountain Reservoir, 1951 and 1952.

perature index, a study was performed to see what degree of accuracy of forecasting of St. Louis Creek could be attained, using only the data from the Weather Bureau cooperative climatological data station at Fraser, Colo., located about 4½ miles downstream from the St. Louis Creek stream gaging station. This weather station is at an open valley at an elevation of 8,560 feet above sea level, and is an example of the type of data usually available to the practicing hydrologist in most drainage basins having an operational significance.

An initial study using daily maximum temperature in a single correlation with snowmelt runoff did not yield operationally useful results. Therefore, the concept worked out in the snowmelt runoff forecast for the Blue River above Green Mountain Reservoir was applied to St. Louis Creek. Data for a total of 185 days, 143 of which were through the peak and 42 of which were after the peak of seasonal snowmelt runoff, were combined for the 1948, 1949, 1950, 1951, and 1952 snowmelt seasons for a test of the method as applied to the 1953 melt season.

Since all of the work done on analysis of snowmelt hydrographs to date had indicated the critical nature of the runoff before and after the peak day, the 6 years of data used in this study were classified in two groups, as tabulated below:

Year	*Through the peak*	*Past the peak*
1948	May 13–June 3	June 4–5
1949	May 15–June 18	June 19–25
1950	May 13–June 17	June 18–28
1951	May 15–June 20	June 21–28
1952	May 25–June 10	June 11–23
1953	May 21–June 14	June 15–27

As was done for the Blue River, maximum daily temperature at Fraser, Colo., was used.

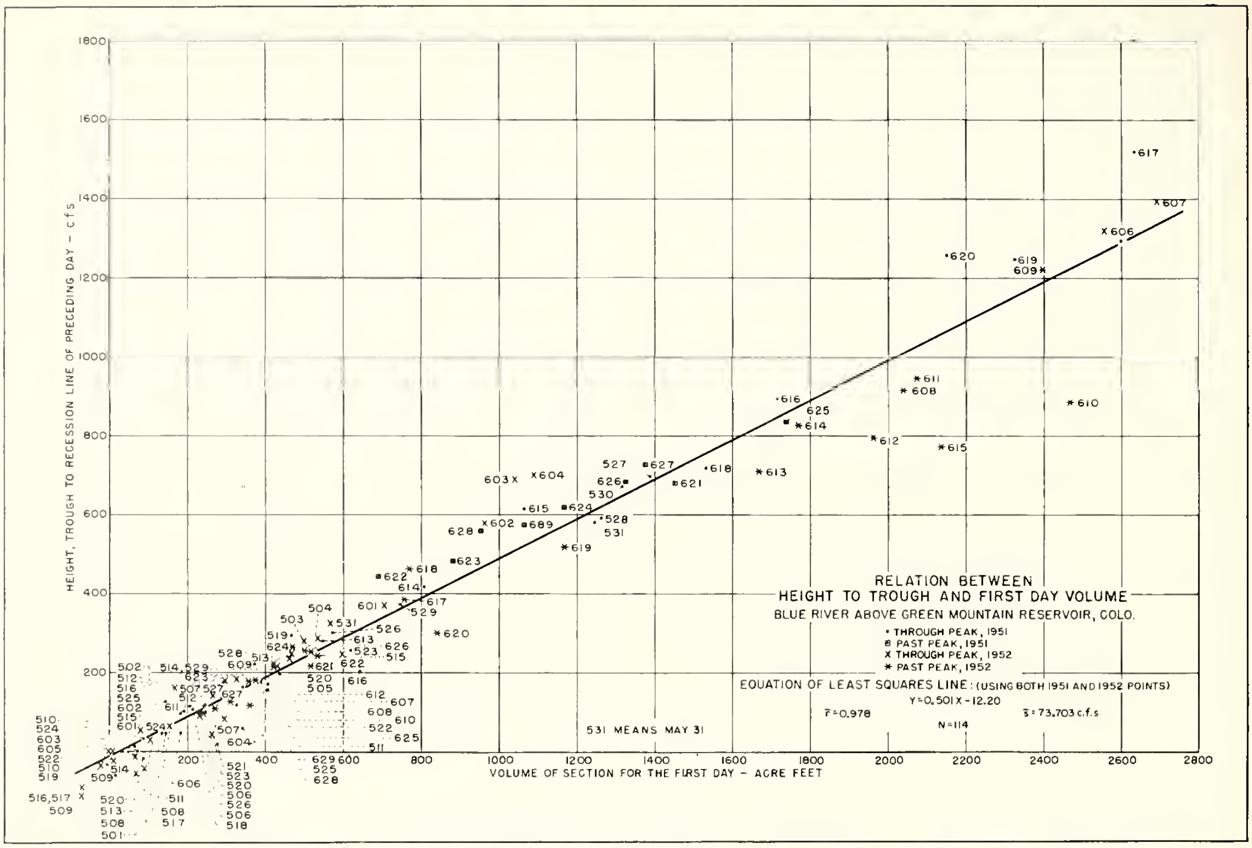

Figure 93. Relation between height to trough and first day volume, Blue River above Green Mountain Reservoir, 1951 and 1952.

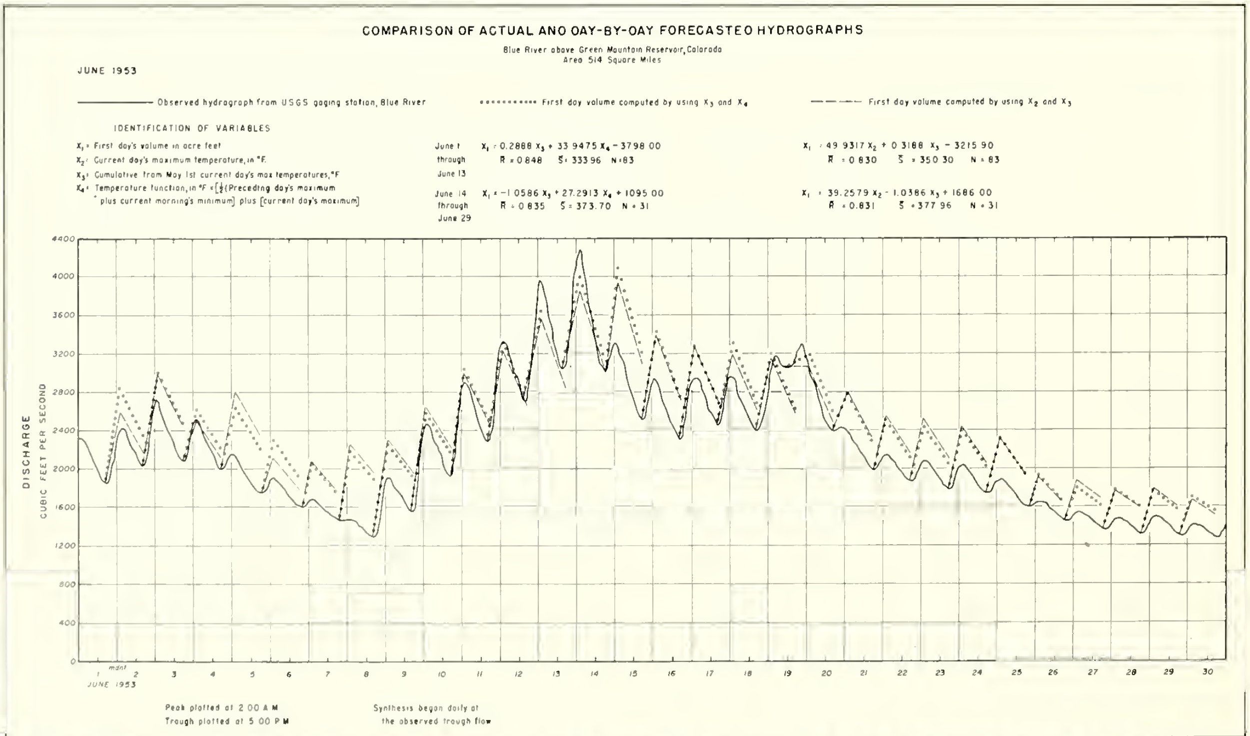

Figure 94. Comparison of recorded and day-by-day forecasted hydrograph for Blue River above Green Mountain Reservoir, 1953.

The following equations were derived:

Through the peak:

$$X_1 = 3.036X_2 + 0.019X_3 - 189.76$$

$$\bar{R} = 0.803 \qquad \bar{S} = 2.258 \qquad N = 143$$

Past the peak:

$$X_1 = 3.891X_2 - 0.043X_3 - 97.68$$

$$\bar{R} = 0.823 \qquad \bar{S} = 2.745 \qquad N = 42$$

in the above equations:

X_1 equals first day's volume in acre-feet

X_2 equals maximum temperature at Fraser, Colo., in degrees Fahrenheit

X_3 equals accumulated maximum temperature from May 1 at Fraser, Colo., in degrees Fahrenheit

It is interesting to note that X_3, the accumulated maximum temperature, possessed a negative sign in the equation for days past the peak as it had done in the Green Mountain Reservoir study. Thus, the accumulated temperature index again represents a relationship to snowmelt runoff which differs from the relationship of the daily maximum and which changes its hydrologic effect upon snowmelt runoff at the time of the peak of the seasonal volume contribution.

As the area covered by snow recedes and the waters released by the melting of snow must travel progressively increasing distances through the subsurface channels to the stream channels, the advance of warm weather with increased temperatures at lower altitudes due to the normal lapse rate operation increases the losses by evapotranspiration. With rising temperatures at the lower elevations coupled with depletion of the snow remaining to be melted at the higher altitudes further up the slopes, the snowmelt waters continue to be absorbed as replenishment for evapotranspirational losses in greater proportion. Whereas a day's snowmelt depends upon the heat available at the snowfield, the day's contribution of snowmelt to runoff is influenced also by the evapotranspirational losses as the melt season progresses.

Table 38 presents the net first-day volumes in acre-feet for the years 1948 through 1952 used in deriving the forecast computations.

In order to forecast the shape of the daily snowmelt hydrograph, the estimated first-day volumes were used in a manner described previously to derive height to peak and height to trough dimensions as measured in c. f. s. from the recession

Table 38—Summary of net first day's volumes in St. Louis Creek near Fraser for 1948 to 1952, inclusive

Date	First day volume in acre-feet				
	1948	1949	1950	1951	1952
May 13	28.772	-------	8.936	--------	--------
14	34.308	-------	12.415	--------	--------
15	36.789	-------	6.698	19.912	--------
16	41.728	-------	17.835	23.484	--------
17	60.042	-------	33.590	12.706	--------
18	35.431	-------	−1.640	12.389	--------
19	52.114	10.092	15.132	25.359	--------
20	67.361	−.006	22.750	23.611	--------
21	64.207	2.436	41.675	23.409	--------
22	62.549	5.457	42.073	30.512	--------
23	45.538	9.731	36.803	27.784	--------
24	19.069	16.600	17.919	13.492	--------
25	41.671	31.317	1.345	22.134	18.375
26	3.886	40.377	−8.227	25.505	16.707
27	47.014	21.747	4.951	70.397	15.239
28	43.714	27.233	15.886	87.626	20.041
29	16.441	22.219	9.596	25.821	39.550
30	64.342	32.342	44.045	84.173	26.263
31	62.688	−.591	50.406	74.473	32.991
June 1	65.103	−.077	62.150	−21.570	36.617
2	87.675	3.146	55.722	−.859	33.759
3	*84.821*	13.555	−14.719	−5.068	106.364
4	63.747	29.871	16.187	13.523	60.397
5	63.812	47.328	53.696	12.125	149.651
6	------	15.675	93.412	15.874	104.293
7	------	11.129	66.573	17.956	109.751
8	------	36.452	5.034	17.845	119.167
9	------	42.476	48.071	9.354	113.863
10	------	38.555	104.307	14.081	*161.530*
11	------	80.027	114.161	5.288	67.442
12	------	109.263	95.808	14.934	127.416
13	------	60.843	105.481	34.383	84.214
14	------	49.061	105.905	38.323	125.284
15	------	76.986	112.959	61.585	158.818
16	------	125.972	97.045	81.642	−10.322
17	------	83.113	*63.767*	188.001	40.374
18	------	*29.714*	27.352	34.145	31.232
19	------	86.862	34.391	33.602	92.977
20	------	72.264	22.011	*115.043*	82.316
21	------	84.456	30.468	22.141	33.836
22	------	68.168	16.187	9.364	18.581
23	------	51.929	34.522	13.023	15.562
24	------	13.979	41.111	64.437	--------
25	------	36.307	26.219	92.920	--------
26	------	-------	26.834	52.415	--------
27	------	-------	20.124	48.256	--------
28	------	-------	18.109	27.404	--------
29	------	-------	--------	26.471	--------

line of the preceding day's trough. Two series of equations were derived, one of which made use of all 185 days available for correlation analyses:

For the peak:

$$Y = 0.808X + 2.35 \text{ (all days)}$$

$$\bar{r} = 0.964 \qquad \bar{s} = 8.319 \qquad N = 185$$

For the trough:

$$Y = 0.358X - 2.61 \text{ (all days)}$$

$$\bar{r} = 0.793 \qquad \bar{s} = 10.304 \qquad N = 185$$

Another series of four equations were grouped in pairs, with separate equations for forecasting

the peak, using the days through the peak amounting to 143 days; and another equation for days past the peak amounting to 42 days. A similar pair of equations was computed for deriving the height to trough.

For the peak:

$Y=0.795X+1.52$ (through the peak)

$\bar{r}=0.972 \quad \bar{s}=7.264 \quad N=143$

$Y=0.836X+5.70$ (past the peak)

$\bar{r}=0.951 \quad \bar{s}=9.909 \quad N=42$

For the trough:

$Y=0.387X-1.64$ (through the peak)

$\bar{r}=0.844 \quad \bar{s}=9.301 \quad N=143$

$Y=0.281X-6.45$ (past the peak)

$\bar{r}=0.728 \quad \bar{s}=9.554 \quad N=42$

In the above six equations, Y equals the height to peak or to the trough and X equals estimated first day's volume, as computed by the multiple-correlation equations using the cumulative temperature index, as described previously.

For the 1953 forecasted season, May 21 through June 14 were considered to be days through the peak, and June 15 through June 27 were days past the peak. The results of the application of the equations to the 1953 forecast are given in table 39. A graphic presentation of this forecast is presented in figure 95.

It will be noted on figure 95 that marked departures between the forecast and the observed hydrographs can be seen to have occurred at the time when rainfall of measurable quantities was re-

Table 39—Comparison between actual and estimated volumes for St. Louis Creek near Fraser, 1953

1	2	3	4	5	6	7	8
Melt of 1953	Residual flow	Actual net first day volume	Actual total flow for day	Estimated net first day volume [1]	Estimated total flow for day	Departure of (6) from (4)	Percent departure
May 21	27	24	51	39	66	15	29. 4
22	50	25	75	34	84	9	12. 0
23	61	26	87	51	112	25	28. 7
24	73	48	121	34	107	−14	−11. 6
25	91	42	133	54	145	12	9. 0
26	106	43	149	61	167	18	12. 1
27	*139*	*74*	*213*	*41*	*180*	*−33*	*−15. 5*
28	*183*	*79*	*262*	*48*	*231*	*−31*	*−11. 8*
29	190	−13	177	7	197	20	11. 3
30	163	31	194	42	205	11	5. 7
31	169	60	229	58	227	−2	−0. 9
June 1	187	54	241	60	247	6	2. 5
2	224	52	276	40	264	−12	−4. 3
3	236	32	268	50	286	18	6. 7
4	232	17	249	48	280	31	12. 4
5	211	16	227	34	245	18	7. 9
6	195	30	225	38	233	8	3. 6
7	193	−1	192	24	217	25	13. 0
8	170	78	248	68	238	−10	−4. 0
9	220	106	326	94	314	−12	−3. 7
10	257	126	383	101	358	−25	−6. 5
11	312	110	422	97	409	−13	−3. 1
12	389	118	507	98	487	−20	−3. 9
13	429	148	577	103	532	−45	−7. 8
14	469	67	536	89	558	22	4. 1
15	417	54	471	84	501	30	6. 4
16	395	59	454	88	483	29	6. 4
17	389	80	469	85	474	5	1. 1
18	*402*	*186*	*588*	*78*	*480*	*−108*	*−18. 4*
19	*524*	*23*	*547*	*−26*	*498*	*−49*	*−9. 0*
20	441	−3	438	30	471	33	7. 5
21	382	13	395	50	432	37	9. 4
22	355	26	381	58	413	32	8. 4
23	337	32	369	63	400	31	8. 4
24	312	16	328	44	356	28	8. 5
25	274	10	284	18	292	8	2. 8
Total*	8, 206	1, 541	9, 747	1, 890	10, 096	655+	
Average*							6. 7

*Does not include amounts for May 27 and 28 and June 18 and 19 which were influenced.
+Total of data without regard to sign.

[1] Using X_2X_3 equations; X_2=maximum temperature at Fraser, Colo., X_3=accumulated maximum temperature.

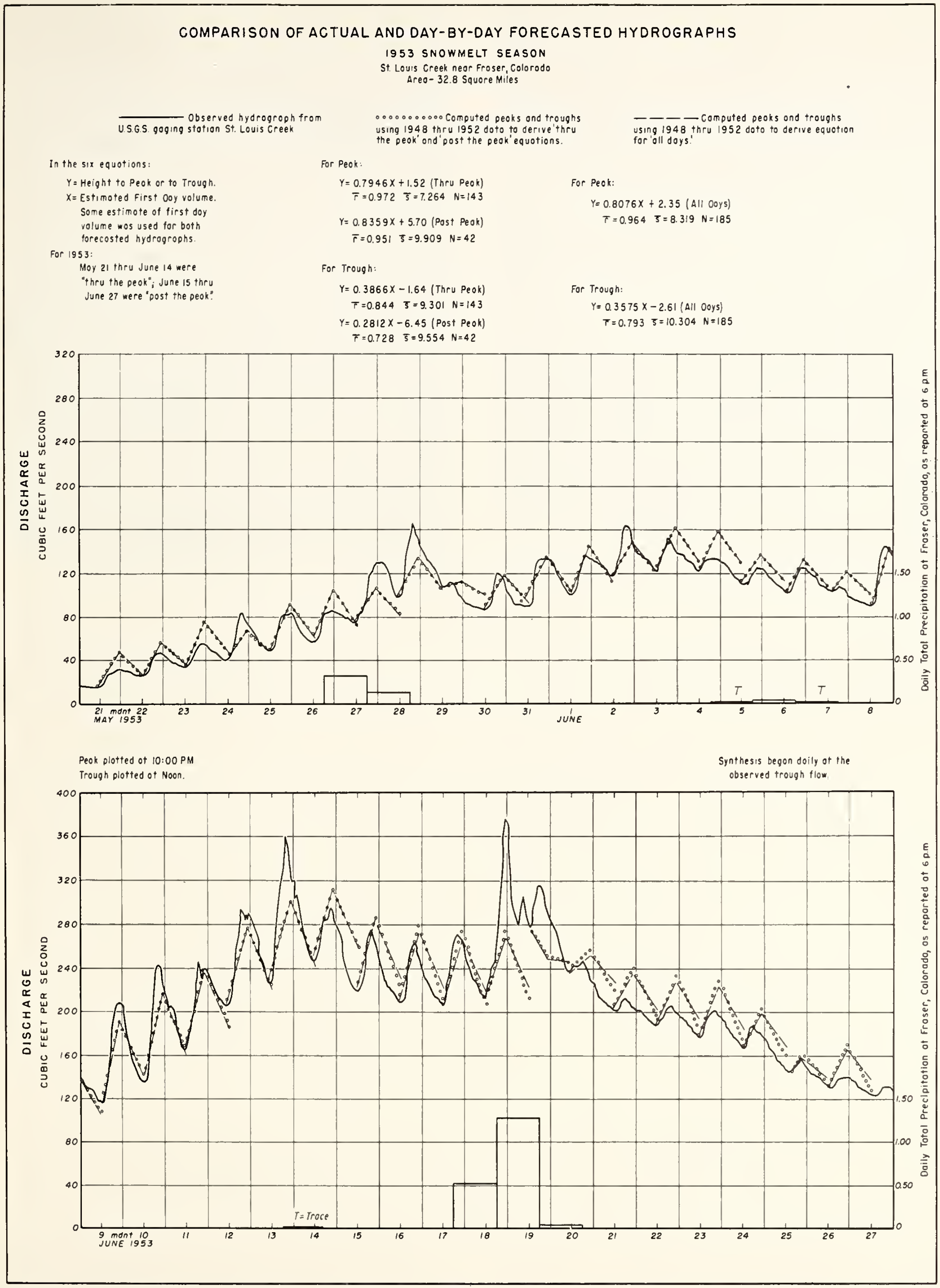

Figure 95. Comparison of recorded and day-by-day forecasted hydrograph for St. Louis Creek near Fraser, 1953.

ported by the Weather Bureau's cooperative station at the town of Fraser, Colo. Because of the spotty character of rainstorms in proximity to the major orographic features to be found in the Fraser Experimental Forest, it is quite likely that the record from Fraser is only a general index of the times of occurrence of, areal distribution of, and total amount of precipitation as it might occur in the St. Louis Creek drainage basin above the stream gaging station. Nevertheless, daily totals of rainfall, as reported from Fraser, Colo., do serve to explain major departures of forecast from observed hydrographs.

In table 39, the days for which there was evidence of contribution to runoff from rainfall were not used in computing the averages of departures from the actual hydrograph. When so computed, the average departure of the forecast from the actual hydrograph for St. Louis Creek, as forecasted from the use of maximum temperatures from the town of Fraser, Colo., alone, was found to be 6.7 percent.

Figure 95 demonstrates that, through the use of the maximum temperature alone at a point considerably removed both in horizontal distance and in elevation from the areas where the snowmelt is taking place, and through the application of the recession concept of snowmelt contribution to runoff, it is possible to forecast the snowmelt hydrograph with practically as much accuracy as was previously demonstrated in forecasting the runoff resulting from snowmelt through the use of multiple factorial considerations either through correlation analyses or physical equations, such as Light's equation. This method of forecasting the day-by-day snowmelt and peaks and troughs of the snowmelt hydrograph has yielded practically as good a forecast on the recession limb, or falling stages, of the snowmelt hydrograph as did more intricate methods on the rising stages of the hydrograph. As is to be noted on figure 95, the accuracy of the forecast for St. Louis Creek for the 1953 snowmelt season, with the exception of those days on which rain fell, is practically uniform for the period before and after the peak of the snowmelt contribution to the seasonal hydrograph.

SECTION 12—SNOWMELT RUNOFF FROM FOOL CREEK

One of the tributaries of St. Louis Creek is Fool Creek, as shown on the map of the Fraser Experimental Forest, figure 2. The drainage area of Fool Creek above the gaging station used in these analyses is 714 acres, or 1.11 square miles. The area-elevation relation is shown in figure 96. An analysis of the hydrograph paralleling the one described in section 8 for St. Louis Creek was performed for Fool Creek.

The derived recession curve for Fool Creek is given in figure 97. It was discovered that Fool Creek possessed a variable recession relationship, yielding a K_r for a 24-hour period of 0.871 for a flow of about 18 c. f. s. This factor increased gradually to a value of $K_r=0.952$ at 1.00 c. f. s. The recession curve, based upon the 1947 snowmelt season analysis, fitted all years of record except for 1944, when the volume of flow was the lowest of record.

The fact of a variable K_r is not unusual to watershed-discharge relationships [65]. However, the range of variation from a snow-fed stream such as Fool and St. Louis Creeks may be greater than is common to streams supplied solely by rainfall. For the latter streams, the water yielded during the recession flow is entirely ground wa-

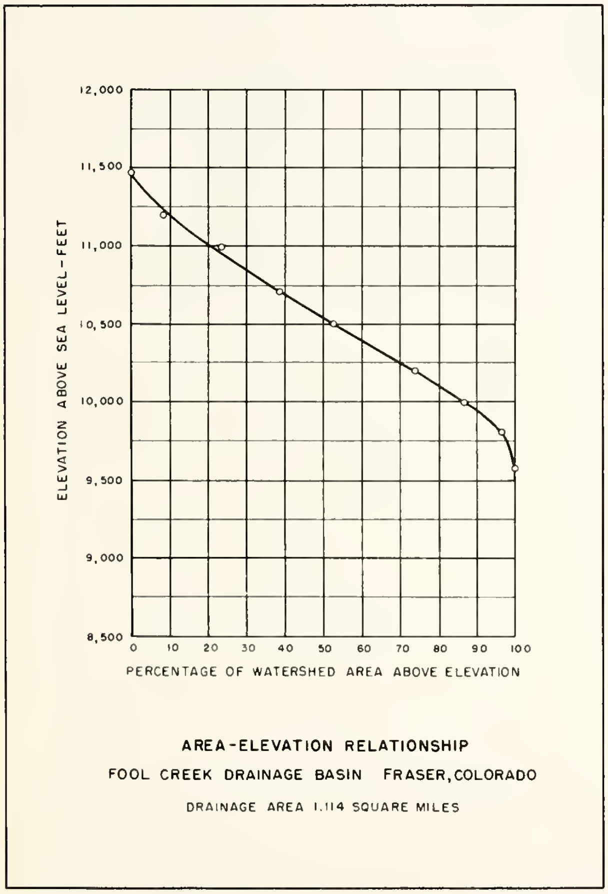

Figure 96. Area-elevation relationship for Fool Creek drainage area.

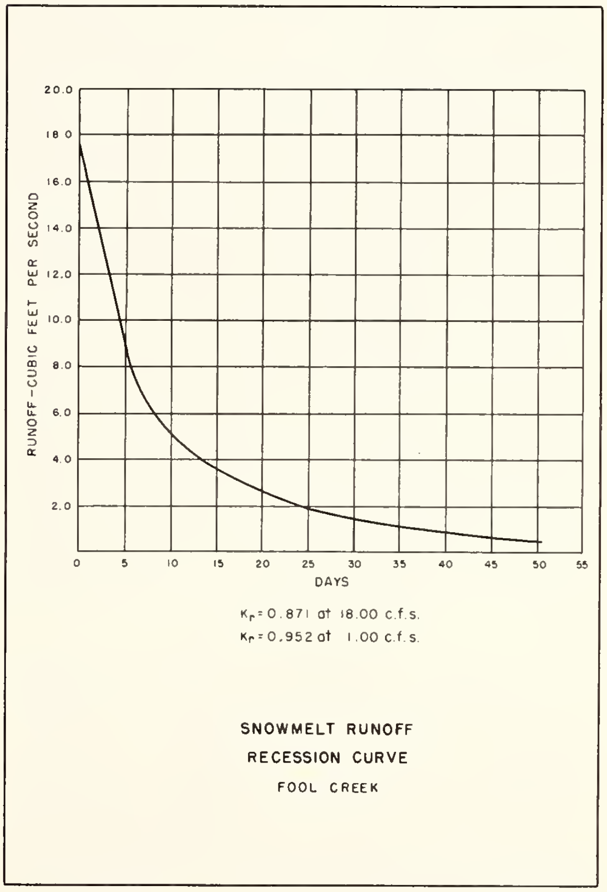

Figure 97. Snowmelt runoff recession curve for Fool Creek.

ter or subsurface in origin. In streams fed mainly by melting of the winter snow pack, this is probably not the case. Instead, the recession curve throughout its higher portion and by the nature of its derivation, should include the effect of the inflow of water draining from the residual snow pack. Part of this drainage may be direct into stream channels and part by way of the soil and rock mantle or entirely by the latter course. In either case, it constitutes an inflow which, declining as the snow pack disappears, results in steepening the slope of the recession curve.

From a different viewpoint, a snow mantle on a watershed may, during its melting, be considered as causing a surcharge of the storage capacity of the watershed. Since melt water drains rapidly from the snow pack, the effect is to steepen the slope of the recession curve to a degree not characteristic when all of the snow has melted and the depletion of the ground water is alone responsible for the recession curve slope. The fact that the K_r associated with Fool Creek appears to vary continuously without breaks between discrete values may be explained by the nondiscrete nature of the disappearance of the snow pack.

In analyzing the hydrograph for Fool Creek, a time lag, as determined from 1948 data, of approximately 3 hours was used. This was found to fit practically all of the records available. Since the recession was variable, the individual day's contributions to the snowmelt hydrograph were determined by drawing the recession line from each day's troughs, and the amount of both the first day's contribution and the recession contribution was determined from the hydrographs by planimetering the areas. Figures 98, 99, and 100 present, respectively, for the 1949, 1950, and 1951 snowmelt periods the hydrographs with the variable recession lines sketched in, together with dew-point temperatures, relative humidities, and air temperature at the Fool Creek hygrothermograph station.

The relation between the first day's volume and the total day's contribution to snowmelt runoff from Fool Creek for 1948 and 1949 is shown in figure 101, in which separate correlation analyses were made using all points, totaling 39, and also for 23 days, including the rising hydrograph and the peak day, and for the 16 days following the day of peak volume contribution. As was true for St. Louis Creek, it was discovered that the relation of the total days' contribution and the volume of the first day's section, when plotted as a double-mass curve, exhibits a change in the slope which occurs at the peak day, as is shown in figure 102. Correlations between the height to peak above the preceding day's recession and total runoff from a day's contribution to snowmelt for Fool Creek are shown in figure 103. The height to trough correlation with the total runoff from a day's contribution for Fool Creek for 1948 and 1949 is shown in figure 104.

It is interesting to note that the general type of relationship between the components of the day's contribution to the snowmelt hydrograph, such as the height to peak, height to trough, and the change in the ratios of these relationships before and after the seasonal peak, is parallel for both basins, although the St. Louis Creek drainage basin is 30 times greater in area than the Fool Creek drainage basin.

Table 40 presents, in tabular form, the trough and the peak flow in c. f. s., the net first day's volume above the preceding day's recession, the recession contribution, and the total runoff of a day's contribution to the snowmelt hydrograph for Fool Creek for 1948 and 1949. In this drainage basin, the first day's volume for both years amounts to 12.4 percent of the total day's contribution to snowmelt runoff.

A summary of the day's contributions to snowmelt, expressed as the volume including recession flows in acre-feet for the snowmelt seasons of 1948, 1949, 1950, and 1951, is given in table 41.

In order to find out how well Light's equation could be transposed to different areas varying not only in size but also in type of cover and exposure in addition to the differences in elevation, a comparison was made between the results of snowmelt contributions to runoff as computed by Light's equation using the data from the wind-tower in the open on West St. Louis Creek. A comparison of the actual runoffs and Light's equation volumes is given in table 42. Basin constant, K, was found to be 1.157 for 1948, 0.889 for 1949, and 1.037 for the combined 1948–49 data.

The above is in the nature of a preliminary analysis of the snowmelt runoff characteristics of Fool Creek. It was introduced into this report on the cooperative snow investigations for purposes of comparison with the concept as applied to drainage basins varying greatly in size from

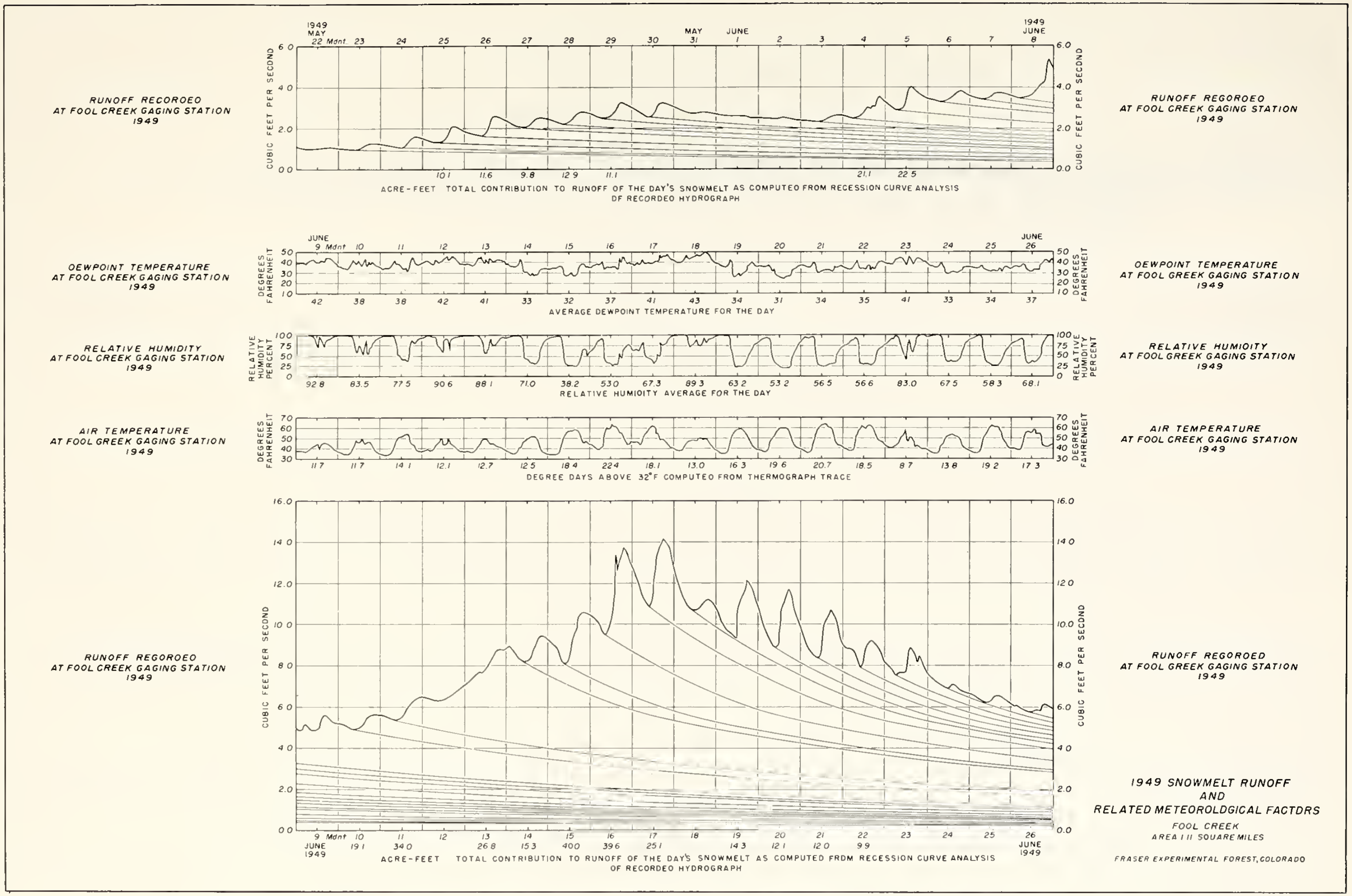

Figure 98. Snowmelt runoff and related meteorological factors, Fool Creek, 1949.

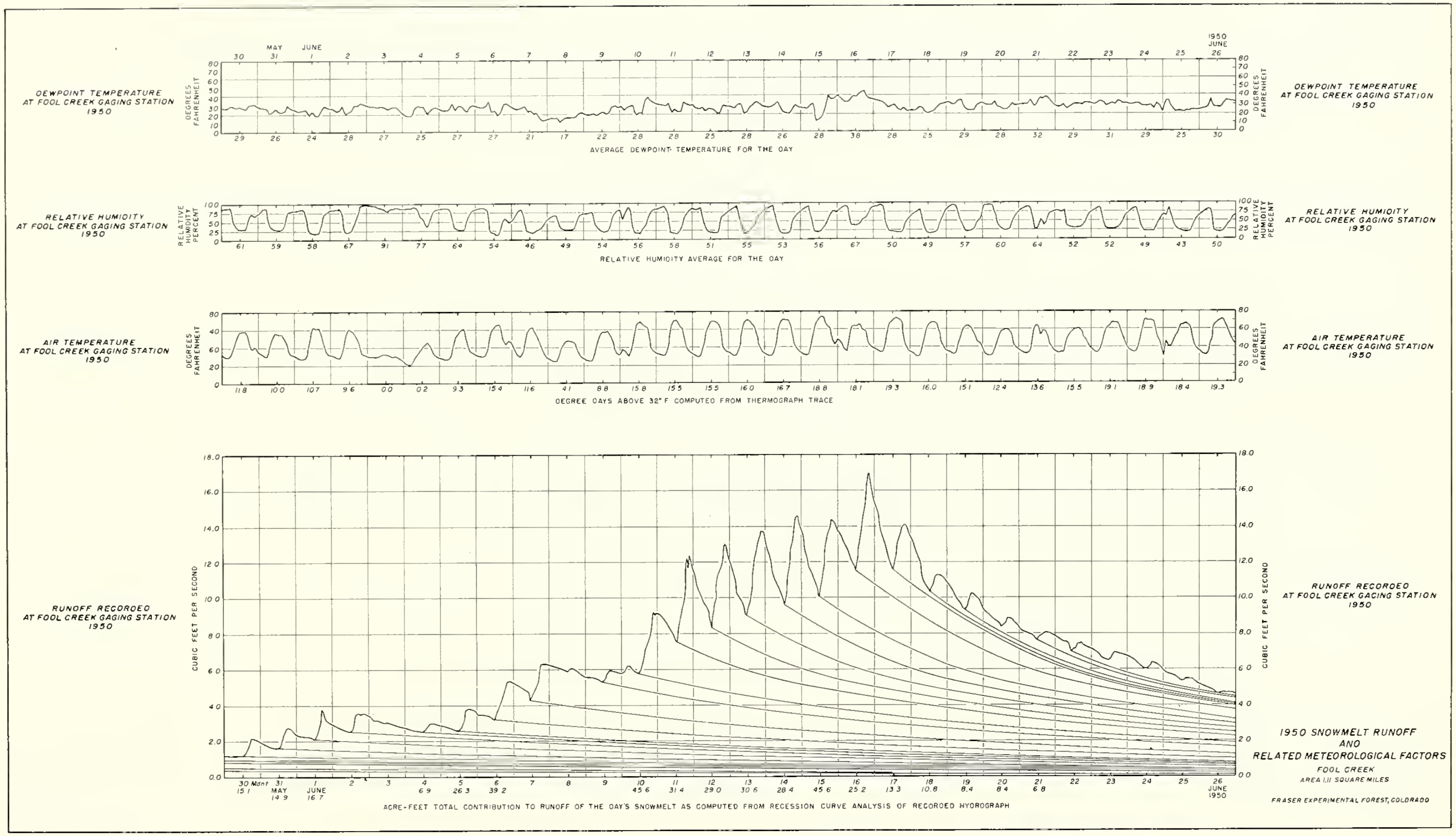

Figure 99. Snowmelt runoff and related meteorological factors, Fool Creek, 1950.

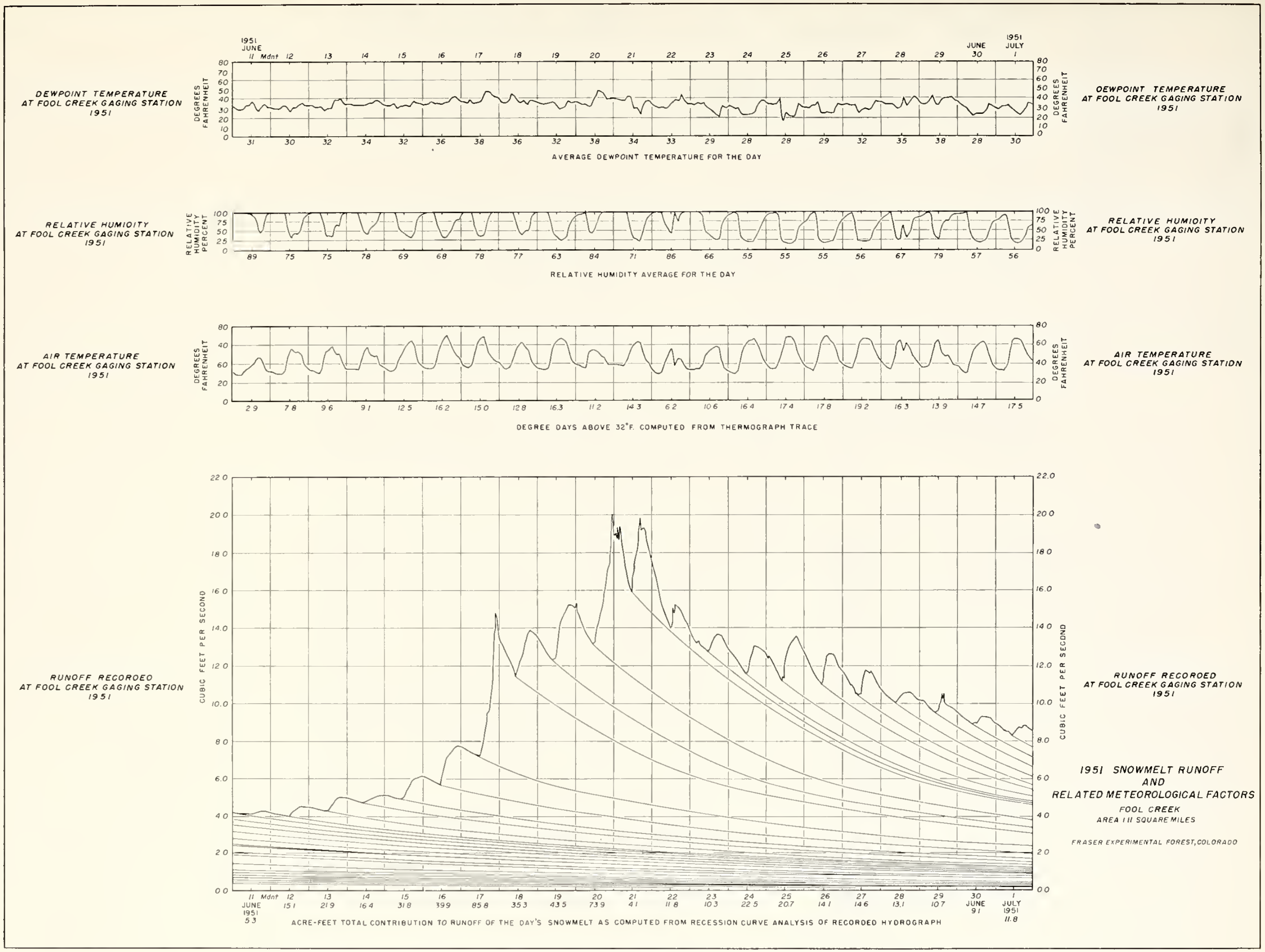

Figure 100. Snowmelt runoff and related meteorological factors, Fool Creek, 1951.

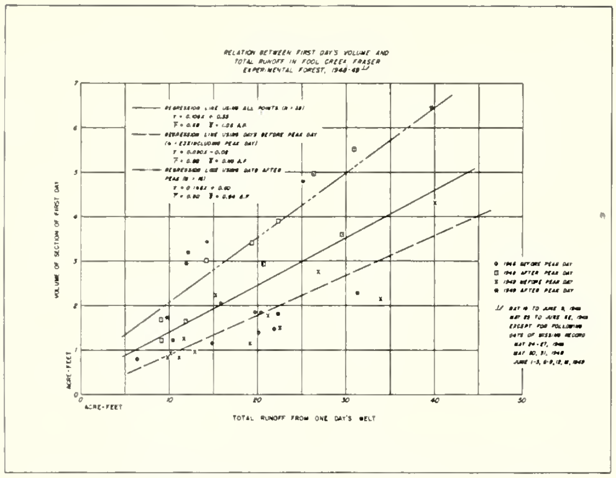

Figure 101. Relation between first day's volume and total runoff from one day's melt, Fool Creek, 1948 and 1949.

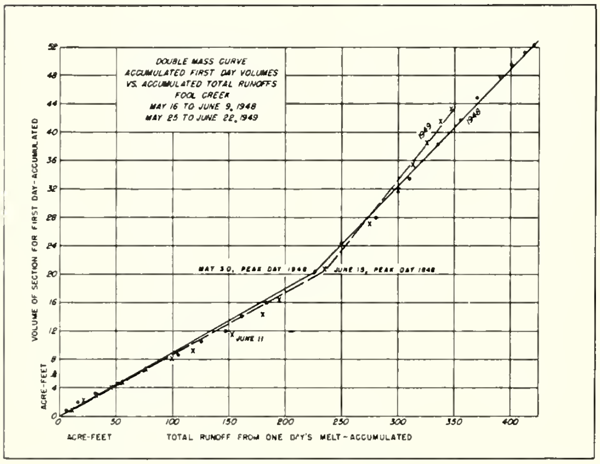

Figure 102. Double mass curve for 1948 and 1949 of accumulated first day volumes vs. accumulated total runoffs in Fool Creek.

Table 40—Summary of discharges and volumes, Fool Creek, 1948 and 1949

Area: 1.11 square miles

Date	Trough (c. f. s.)	Peak (c. f. s.)	Net first day volume above recession (acre-feet)	Volume of recession contribution (acre-feet)	Total runoff day's contribution (acre-feet)
1948					
May 16	0. 8	1. 5	0. 8	5. 6	6. 4
17	1. 2	2. 2	1. 2	9. 2	10. 4
18	1. 6	2. 5	1. 2	13. 8	15. 0
19	2. 0	3. 2	1. 4	18. 7	20. 1
20	2. 5	4. 0	1. 8	20. 5	22. 3
21	3. 0	4. 6	2. 3	29. 0	31. 3
22	3. 8	5. 4	1. 8	17. 9	19. 7
23	4. 0	5. 1	1. 5	20. 3	21. 8
28	5. 8	7. 1	2. 0	13. 8	15. 8
29	6. 0	7. 1	1. 8	18. 6	20. 4
30	6. 1	9. 1	4. 6	39. 7	44. 3
31	7. 8	10. 1	3. 9	18. 5	22. 4
June 1	8. 1	10. 3	3. 6	26. 0	29. 6
2	8. 8	12. 5	5. 5	25. 4	30. 9
3	9. 6	13. 2	5. 0	21. 4	26. 4
4	9. 8	12. 1	3. 4	16. 0	19. 4
5	9. 3	11. 4	3. 0	11. 2	14. 2
6	9. 0	11. 2	2. 9	17. 8	20. 7
7	9. 0	10. 2	1. 7	7. 3	9. 0
8	8. 4	9. 2	1. 6	10. 3	11. 9
9	8. 0	8. 9	1. 2	7. 9	9. 1
1949					
May 25	1. 3	2. 1	0. 9	9. 2	10. 1
26	1. 6	2. 6	1. 3	10. 3	11. 6
27	2. 0	2. 5	. 8	9. 0	9. 8
28	2. 2	2. 8	1. 0	11. 9	12. 9
29	2. 5	3. 2	. 8	10. 3	11. 1
June 4	2. 4	4. 0	1. 8	19. 3	21. 1
5	2. 8	3. 9	1. 5	21. 0	22. 5
10	5. 0	5. 6	1. 2	17. 9	19. 1
11	5. 4	6. 5	2. 2	31. 8	34. 0
13	7. 6	8. 9	2. 8	24. 0	26. 8
14	8. 2	9. 4	2. 2	13. 1	15. 3
15	8. 1	10. 6	4. 3	35. 7	40. 0
16	9. 5	13. 7	6. 4	33. 2	39. 6
17	10. 9	14. 1	4. 8	20. 3	25. 1
19	9. 4	12. 1	3. 4	10. 9	14. 3
20	8. 9	11. 7	3. 2	8. 9	12. 1
21	8. 4	10. 7	2. 9	9. 1	12. 0
22	8. 0	9. 2	1. 7	8. 2	9. 9

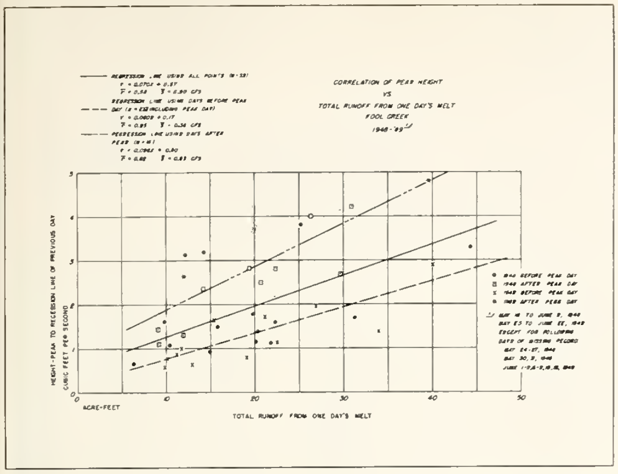

Figure 103. Relation between height to peak and total runoff from one day's melt, Fool Creek, 1948 and 1949.

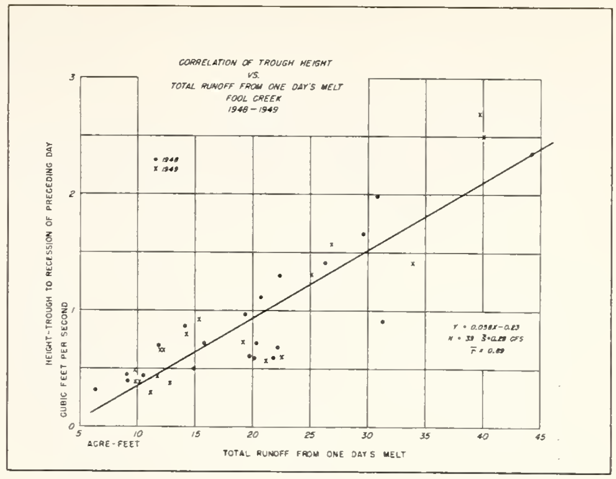

Figure 104. Relation between height to trough and total runoff from one day's melt, Fool Creek, 1948 and 1949.

Table 41—Summary of each day's total runoff volume including recession, Fool Creek, 1948 to 1951, inclusive

Area: 1.11 square miles

1948		1949		1950		1951	
Date	Runoff (acre-feet)	Date	Runoff (acre-feet)	Date	Runoff (acre-feet)	Date	Runoff (acre-feet)
May 16	6.4	May 25	10.1	May 30	15.1	June 11	5.3
17	10.4	26	11.6	31	14.9	12	15.1
18	15.0	27	9.8	June 1	16.7	13	21.9
19	20.1	28	12.9	4	6.9	14	16.4
20	22.3	29	11.1	5	26.3	15	31.8
21	31.3	June 4	21.1	6	39.2	16	39.9
22	19.7	5	22.5	10	45.6	17	85.8
23	21.8	10	19.1	11	31.4	18	35.3
28	15.8	11	34.0	12	29.0	19	43.5
29	20.4	13	26.8	13	30.6	20	73.9
30	44.3	14	15.3	14	28.4	21	4.1
31	22.4	15	40.0	15	45.6	22	11.8
June 1	29.6	16	39.6	16	25.2	23	10.3
2	30.9	17	25.1	17	13.3	24	22.5
3	26.4	19	14.3	18	10.8	25	20.7
4	19.4	20	12.1	19	8.4	26	14.1
5	14.2	21	12.0	20	8.4	27	14.6
6	20.7	22	9.9	21	6.8	28	13.1
7	9.0					29	10.7
8	11.9					30	9.1
9	9.1					July 1	11.8

Table 42—Comparison of runoff volume with snowmelt computed by Light's equation, Fool Creek, 1948 and 1949

Area = 1.11 square miles

1948	Melt computed by Light's equation	Runoff volume measured	Departure of computed from measured volume		1949	Melt computed by Light's equation	Runoff volume measured	Departure of computed from measured volume	
	Inch	*Inch*	*Inch*	*Percent*		*Inch*	*Inch*	*Inch*	*Percent*
May 16	0. 134	0. 108	+0. 026	+24. 1	May 25	0. 150	0. 170	−0. 020	−11. 8
18	. 376	. 253	+. 123	+48. 6	26	. 293	. 197	+. 096	+48. 7
19	. 487	. 340	+. 147	+43. 2	27	. 292	. 166	+. 126	+75. 9
20	. 369	. 377	−. 008	−2. 1	June 4	. 167	. 357	−. 190	−53. 2
21	. 422	. 528	−. 106	−20. 1	5	. 326	. 380	−. 054	−14. 2
22	. 258	. 333	−. 075	−22. 5	10	. 246	. 323	−. 077	−23. 8
23	. 167	. 369	−. 202	−54. 7	15	. 340	. 676	−. 336	−49. 7
28	. 168	. 267	−. 099	−37. 1	16	. 774	. 669	+. 105	+15. 7
29	. 119	. 345	−. 226	−65. 5	17	. 704	. 424	+. 280	+66. 0
30	. 455	. 748	−. 293	−39. 2	19	. 499	. 242	+. 257	+106. 2
31	. 439	. 378	+. 061	+16. 1	20	. 492	. 205	+. 287	+140. 0
June 1	. 491	. 500	−. 009	−1. 8					
2	. 524	. 523	+. 001	+. 2	Totals	4. 283	3. 809	+. 474	+12. 4
3	. 262	. 445	−. 183	−41. 1					
4	. 207	. 329	−. 122	−37. 1					
5	. 379	. 240	+. 139	+57. 9					
Totals	5. 257	6. 083	−. 826	−13. 6					

Basin constant, $K=\frac{6.083}{5.257}=1.157$ based on 1948 data.

Basin constant, $K=\frac{3.809}{4.283}=0.889$ based on 1949 data.

Basin constant, $K=\frac{9.892}{9.540}=1.037$ for combined 1948 and 1949.

that of Fool Creek. There is a continuing investigation being conducted at Fool Creek by the Forest Service on the influence of silvicultural practices and timber harvesting upon the water yield from the drainage basin. Subsequent to the termination of intensive analyses as part of the cooperative snow investigations program, the Forest Service has installed additional gaging stations, further subdividing the 1.11-square-mile drainage basin of Fool Creek. Further reports upon Fool Creek, its forest management and hydrology, will be forthcoming as part of the Forest Service's continuing research in watershed management.

SECTION 13—EFFECT OF INSTRUMENT ERRORS

The influences which errors in recorded or tabulated data have upon the usefulness of results of computations based on those data would reasonably be expected to vary with the type of analysis being performed. In order to ascertain the effect of various errors, computations were performed using both the physical approach and the statistical approach to snowmelt-streamflow computations under assumed conditions of hygrothermograph instrument error. The results of these analyses are summarized in table 43. In this table, errors of measurement of various magnitudes on the hygrothermograph chart were assumed due to the instrument not being in proper adjustment with respect to the printed chart scales for whatever reason, and assuming that the chart had not been properly seated on the hygrothermograph drum.

It will be noted that various errors of both temperature and of relative humidity exert influences of dissimilar magnitude upon the computed day's contribution to snowmelt runoff depending upon the mathematical expression in which such data are used. Thus, a +10-percent error in relative humidity caused Light's results to be 40 percent high whereas in multiple correlation Equation 6, the computed snowmelt runoff was about 15 percent high; while in Equation 19 (in which relative humidity has a small influence) the error would be only about 2½ percent.

The error due to improper placement of a chart was especially interesting. Thus, when a minus 1° F error in temperature was coupled with a minus 2-percent error in relative humidity due to the chart riding too high on the drum, the combination would yield an error of minus 9 percent in Equation 6. An error of minus 3° F and minus 6-percent relative humidity would result in a minus 26-percent error to the computed snowmelt in Equation 6.

The conversion of relative humidity and temperature data to dewpoint presupposes exact time phase adjustment of the two records on the hygrothermograph chart. If the trace of the hygrothermograph pen is recorded ahead or behind the relative humidity trace, the wet and dry "bulb" temperatures used in interpolations in psychrometric tables will be out of phase, and the resulting dewpoints can, at times, be highly fictitious.

The effect of averaging in the derivation of derived values is illustrated by the evaporation-condensation portion of Light's equation. This por-

Table 43—Effect of errors in instrument adjustment

St. Louis Creek, near Fraser, Colo.—May 20, 1948

Source of error	Error in measurement		Percent error in computed day's contribution to snowmelt runoff		
	Temperature °F	Relative humidity (percent)	Light's equation	Equation 6	Equation 19
Instrument not being in proper adjustment with respect to printed chart scales	----------	+10	+40.0	+14.9	+2.4
	0	+6	+25.0	+8.9	+1.4
	----------	+3	+14.0	+4.4	+.7
	+3	----------	+40.7	+20.7	+15.5
	+1	----------	+13.6	+6.9	+6.5
	0	0	0	0	0
	−1	----------	−13.7	−6.1	−5.8
	−3	----------	−31.1	−17.6	−16.6
	----------	−3	−9.0	−4.5	−.7
	0	−6	−21.0	−8.9	−1.4
	----------	−10	−38.0	−14.9	−2.4
Chart not correctly placed in recorder drum	−1	−2	----------	−9.1	----------
	−3	−6	----------	−26.5	----------

Table 44—Comparison between 6-hour average vapor pressure differential obtained by averaging dewpoints and obtained directly from hourly values of vapor pressure

West St. Louis Creek—May 15, 1950

Time	Direct conversion			Averaging of data				Percent error
	6-hour average vapor pressure in inches	6-hour average vapor pressure in MB (e)	6.11–e	6-hour average dewpoint temperature	Average vapor pressure in inches	Vapor pressure in MB (e)	6.11–e	
6 a. m.	0.158	5.35	0.76	29.17	0.157	5.32	0.79	+4
12 noon	.157	5.32	.79	29.00	.157	5.32	.79	0
6 p. m.	.178	6.03	.08	31.67	.180	6.10	.01	−88
12 p. m.	.178	6.03	.08	31.83	.180	6.10	.01	−88
Total			1.71				1.60	−6

tion of Light's equation uses 6-hour-average vapor pressure in millibars associated with the dewpoint temperature which is computed from relative humidity and temperature through the use of psychrometric tables. The 6-hour-average vapor pressure can be determined from the average of the six hourly values of dewpoints, or directly by converting each hourly dewpoint to vapor pressure and averaging the six hourly values of vapor pressure. A comparison of the values attained by the two approaches as they affect the evaporation-condensation variable for May 15, 1950, is shown in table 44. In this example, the use of the average of the six hourly values of dewpoint results in a small error of only minus 6 percent in the daily total evaporation.

It is evident that Light's equation is very sensitive to errors both in temperature and relative humidity. The percent error in observations of wind travel will produce the same percent error in the melt values computed from Light's equation. However, such errors were not considered since no facilities were available in the course of these snow investigations to supply a reference standard for the accuracy of wind data as long as the anemometers and recorder circuits appeared to be functioning. Wind recorder charts were corrected when necessary by comparison with totalizer dials built into the anemometer housing.

In view of the potential importance of Light's equation to flood hydrology applications, the following special study was made to test the accuracy of hygrothermograph chart transcriptions of relative humidity by comparison with psychrometer readings.

A study of the available charts indicated that for the period January 2, 1950, through July 30, 1950, the same hygrothermograph Serial No. 4548 had been in use at Shadow Mountain Government Camp, and an almost continuous record of psychrometric readings and recorded relative humidities was available. Before being put into service, the clock movement had been conditioned for cold weather by the Geological Survey's Rocky Mountain Instrument Shop, a new hair element had been installed, and the instrument had been calibrated in the controlled humidity rooms of the Bureau of Reclamation's Division of Engineering Laboratories during the period November 14, 1949. The calibration data are given in table 45.

In August 1950, after it was taken out of service at Shadow Mountain Camp, it was recalibrated with the results shown in table 46. From the calibrations, reasonable accuracy would be expected from the hygrograph record during the period under review.

An examination of the charts for the period January 2 through July 30, 1950, showed that the trace in general was good, although occasionally readings of over 100 percent were recorded. No reason for this could be found. However, these discrepancies were not regarded as being significant because the hair element is recognized as being accurate only between the range of 20- to 95-percent relative humidity.

The relative humidity at 4:30 p. m. each day was read from the chart trace, care being taken to adjust for any errors in the time setting.

The psychrometer wet- and dry-bulb readings, made at 4:30 p. m. each day, were also tabulated and the relative humidity was calculated by use of a psychrometric calculator for a barometric pressure of 23 inches or 7,098 feet. When this computation was made in 1954, neither tables nor special calculators were available for barometric pressures less than 23 inches of mercury which could be applied to the actual elevation of the point of record, 8,392 feet.

Table 45—Pre-service calibration of hygrothermograph serial No. 4548

Date	Time	Number of room	Temperature of room	R. H. of instrument	R. H. from psychrometer	R. H. of control room setting
			° F	*Percent*	*Percent*	*Percent*
November 15, 1949	1:15 p. m.	16	70	40	51 52	50
November 16, 1949	8:00 a. m.	12	69	87	100	100
November 16, 1949	12:40 p. m.	Rocker arms and pen adjusted to 50 percent controlled Room 16				
November 17, 1949	8:45 a. m.	16	70	49. 5		49
November 17, 1949	10:20 a. m.	12	69	99		100
November 17, 1949	3:42 p. m.	1	39½	67	[1] 64 [1] 67	
November 18, 1949	10:30 a. m.	1	39½	63	65 63	

[1] Three readings.

Table 46—Post-service calibration of hygrothermograph serial No. 4548

Date	Time	R. H. from instrument	R. H. of control room setting	Number of room
		Percent	*Percent*	
Aug. 10, 1950	8:15 a. m.	48	50	16
Aug. 11, 1950	10:30 a. m.	100	100	12
Aug. 15, 1950	10:15 a. m.	104	100	12
Aug. 16, 1950	8:25 a. m.	49	51	16

The 182 pairs of relative humidity values are plotted on figure 105 and show a very good correlation, $\bar{r}=0.961$, when the values below 20-percent and above 95-percent psychrometric relative humidity were neglected.

The points shown on figure 105 are identifiable as to the month. Significant bunching of data is not noted for any one of the months, although most of the points below 20-percent relative humidity on the Y axis are for the dry months of June and July.

Points which are outstandingly poor in correlation were then examined in an effort to select a parameter which would explain their departures. In some cases, a rapid temperature change about 4:30 p. m. appeared relevant, but no general parameter based on this could be established. The difference in maximum and minimum temperatures during the day was also tried but appeared valueless as a parameter. As pointed out in appendix A, the scatter of the points illustrates that hygrograph instrument adjustments should not be made in the field solely on the basis of a few psychrometer readings.

In general, it was concluded from this study that confidence could be placed in hygrothermograph records of relative humidity between the psychrometric values of 20- and 95-percent relative humidity, provided the instrument was carefully adjusted before use, calibrated before and after use, and operated correctly in the field without its setting being interfered with by the observer.

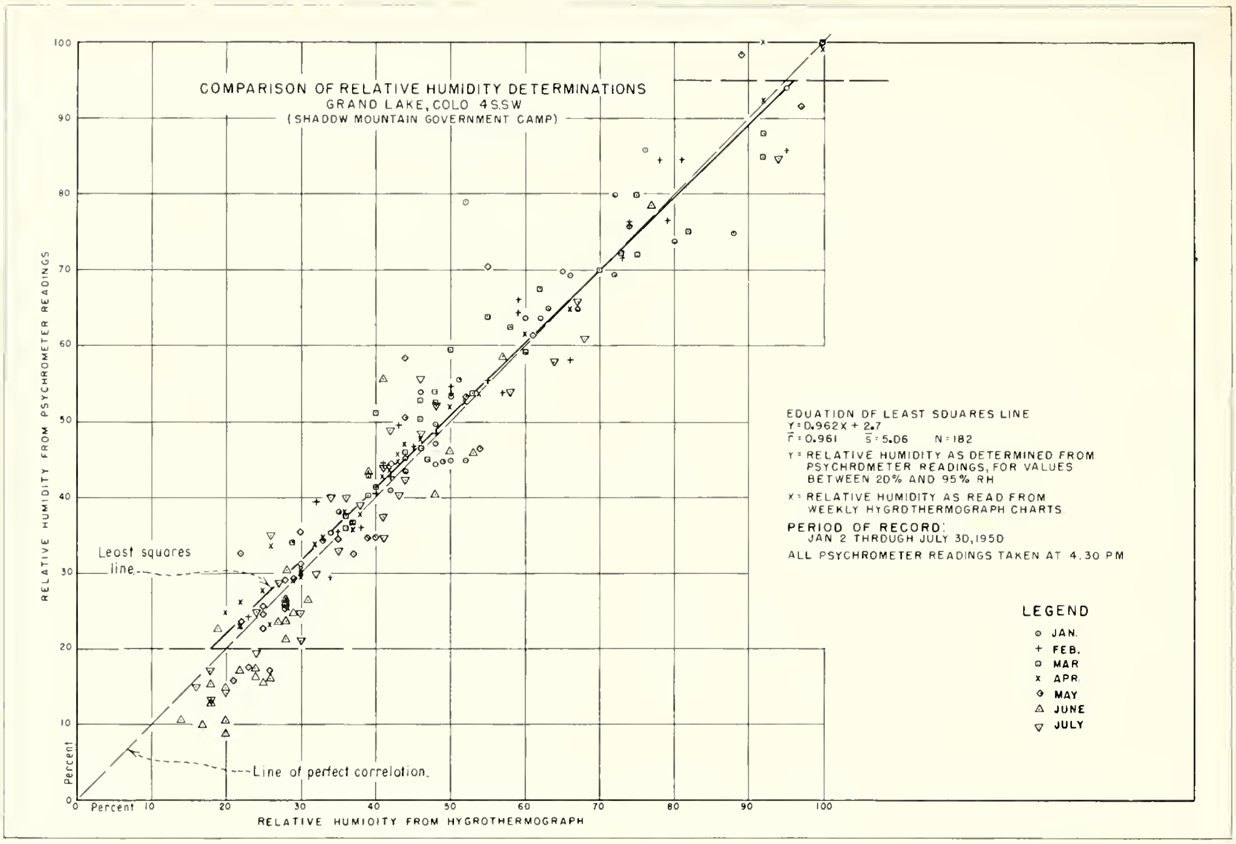

Figure 105. Comparison between hygrograph and psychrometer relative humidity readings.

SECTION 14—SUMMARY

In the Western States the melting of snow and the production of runoff from snowmelt during a short period in the spring not timed to yield water that is needed for crop production, hydroelectric power generation, municipal water and other multiple purpose objectives, has forced the development of an irrigation economy and reservoir control management of the water resources in those drainage basins in which there is a marked seasonal variation in the distribution of the precipitation.

As the objectives of the Bureau of Reclamation and of the Forest Service both relate to the efficient utilization of water resources, these two agencies collaborated during the snowmelt season 1947 through 1953, on a cooperative snow investigation at the Fraser Experimental Forest near Fraser, Colo. This Forest lies 65 miles west and north of Denver, Colo. The objectives of these snow investigations were:

(a) Measurement of the total winter precipitation.

(b) Determination of the water equivalent of snow in storage in a drainage basin, its distribution over the area, and its disappearance as the melt season progresses.

(c) Development of methods of rapid evaluation of heat availability for use in both project planning and operational consideration of runoff from snowmelt.

(d) Development of a technique capable of routine use, (1) to account for, and, (2) to forecast losses from snow storage which may occur either as snowmelt or as evaporation.

The foregoing objectives are related to the development of new methods and improvement of existing methods of forecasting runoff from snowmelt as applied to both forecasts of seasonal water yield volumes and also to forecasting rates of runoff from snowmelt.

The report reviews the literature as it pertains to the behavior of natural drainage basins and describes the climate, topography, geology, soils, native vegetation, and stream flow of the Fraser Experimental Forest. The analyses deal for the most part with that portion of the drainage of St. Louis Creek, 32.8 square miles in area, which lies within the Fraser Experimental Forest, and with Fool Creek, a tributary of St. Louis Creek, with a drainage area of 1.11 square miles.

A comparison of the results of various methods of computing degree days as an expression of heat available, based upon air temperature alone, showed that in the central Rocky Mountain area the degree days based upon the daily maximum temperature alone gave the best correlation with the actual thermograph trace.

Experience with a network of Sacramento-type seasonal storage precipitation gages indicated that such gages in their present state of development did not indicate very well the precipitation of the winter season as judged by the comparisons between the water equivalents of storage increments and of snow sampling.

The report describes in detail the disappearance of snow as the 1950 melt season progressed. The results of this snow disappearance study indicate that for specific drainage basins, improved water management operations could result from a knowledge of the rate of disappearance of snow cover in relation to rates and volumes of snowmelt streamflow.

A recession analysis of snowmelt runoff was developed based on the field observation that there is no watershed-wide surface runoff from snowmelt. It was reasoned, therefore, that the hydrograph recession at the end of the snowmelt season should apply to the contribution of each day's snowmelt to the total flow, since subsurface flow follows Darcy's law rather than the laws of hydraulics of overland flow. Since there is practically no surface runoff from snowmelt, the individual day's contribution to the total discharge is a summation of flows of water through a porous medium. Based upon this concept, the daily snowmelt hydrograph was divided into two principal components, the first day's contribution and the recession volume contribution. This recession

analysis concept is illustrated with detailed analyses of both St. Louis Creek and Fool Creek snowmelt hydrograph.

Both physical and statistical approaches were used in analyses of the snowmelt hydrograph and forms a basis for forecasting rates of runoff from snowmelt. Light's equation involving an eddy conductivity concept based upon the theory of atmospheric turbulence was used for the physical approach. This equation accounts for heat from the air as supplied to the snow surface by wind movement and to the heat supplied or abstracted by the condensation of water vapor or by evaporation of snow. Logarithmic distribution of wind velocities in relation to height above ground was verified and possible evaporation losses from the snow in storage were computed through Light's equation.

A procedure based upon a combination of the recession concept, synthesis of the snowmelt hydrograph, and of heat availability derived from Light's equation, permitted forecasting rates of runoff from snowmelt, even for the complex conditions such as would occur on a drainage basin on which runoff from snowmelt was being released concurrently with runoff resulting from rainfall.

The significance of errors, either in individual items of data or in errors in more than one item pertaining to either physical or statistical analyses and forecasts, were analyzed, and their importance to the accuracy of the end results was described.

The first part of the Appendix is a detailed discussion of instrument operation and techniques, not available elsewhere in any known publication pertaining to hydrology under winter conditions. The second part of the Appendix presents examples of basic data gathered both at the Fraser Experimental Forest and elsewhere in the course of these investigations.

The concepts verified and techniques developed in the course of this cooperative snow investigation have been used widely in conjunction with the computation of design floods in connection with the spillway capacities of a large number of dams. The rate-of-runoff forecasting technique has been applied in the development of methods of reservoir operation and river control for an increasing number of projects. The introduction, as yet in the exploratory stages, of the recognition of snow evaporating versus snow melting conditions as the melt season progresses, offers promise of significantly improving the accuracy of seasonal water-yield forecasts. The recognition of the complex interaction of solar radiation and wind movement has led to a redesign of experiments dealing with the influence of forest management on the water yield of natural drainage basins. The Forest Service is continuing watershed management research at the Fraser Experimental Forest with the objective of developing more efficient techniques of forest management insofar as their effect on the water resources is concerned.

APPENDIX A—INSTRUMENTATION

Setting up instruments in the Fraser Experimental Forest for these cooperative investigations was limited to the number, type, and installation that would be practical to use in an operating basin. Figure 2 shows the areal distribution of the stations, while elements observed at each station, type of instruments used, and years of record are summarized in table 47.

Because of lack of power supply at the Forest Headquarters, the solar radiation recorder was operated first at the Bureau of Reclamation's Shadow Mountain Government Camp approximately 21 miles due north of the Forest and later was moved to the Granby Pumping Plant about 19 miles north of the forest.

The greatest concentration of instruments was at the West St. Louis Station, as shown on figures 35 and 106. The two 45-foot windtowers, one in a large open meadow and the other in the forest, had anemometers mounted at the top, middle, and near the base of each. Wind velocities from the six anemometers and wind direction at the top of the tower in the open were recorded by an electrical operations recorder. A weather shelter near the tower in the open contained a hygrothermograph, crank-type psychrometer, and maximum and minimum thermometers. Three shielded 8-inch precipitation gages were installed in the open area where weekly snow samples were also taken.

At the Headquarters Station (figure 107), an

Figure 106. Windtower installation in the open at West St. Louis Creek Station. April 1950.

Table 47 —Instrumentation of the Bureau of Reclamation-Forest Service cooperative snow investigation [1]

Element	Instrument	Location									
		Headquarters	West St. Louis	Upper West St. Louis	East St. Louis	Fool Creek	St. Louis Pass	Lower St. Louis	Iron Creek	Range Creek	Grand Lake [2]
Air temperature.	Maximum-minimum thermometers.	1946–53	1948–50	-------	1947	1949–53	-------	-------	-------	-------	-------
	Thermograph [3]	1946–53	1948–50	-------	1947	1949–53	-------	-------	-------	-------	-------
Relative humidity.	Psychrometer (crank type).	1949–53	1948–50	-------	-------	-------	-------	-------	-------	-------	-------
	Hygrograph [3]	1947–53	1948–50	-------	-------	1949–53	-------	-------	-------	-------	-------
Wind travel	Anemometer with operations recorder.	-------	1948–50 [6]	-------	-------	-------	-------	-------	-------	-------	-------
Wind direction	Wind vane	-------	1949–50	-------	-------	-------	-------	-------	-------	-------	-------
Precipitation (seasonal).[4]	Sacramento storage gage.	-------	-------	1947–50	1947–50	-------	1947–50	-------	1947–50	1947–50	-------
Precipitation (weekly).	W. B. type 8-inch can.	-------	1949–50	-------	1943–53	1946–53	-------	-------	-------	-------	-------
Precipitation intensity.	Recording gage.	1946–53	-------	-------	1946–53	1946–53	-------	-------	-------	-------	-------
Stream flow	Water stage recorder.	-------	-------	-------	1946–53	1946–53	-------	1946–53 [5]	-------	-------	-------
Snow water	Snow tube	-------	-------	-------	1946–53	1946–53	1947–50	1946–53	1947–50	1947–50	-------
Solar radiation	Pyrheliometer with recording potentiometer.	-------	-------	-------	-------	-------	-------	-------	-------	-------	1948–53
Soil moisture	Shovel, scales and oven.	-------	-------	-------	-------	-------	-------	1947–50	-------	-------	-------

[1] In all years, observations were from about April 1 to October 1, except for year-long records from storage precipitation gages and solar radiation station.
[2] All stations but this one were within Fraser Experimental Forest.
[3] Thermograph and hygrograph combined in hygrothermograph.
[4] Also monthly, during spring.
[5] Recorded all year.
[6] Included measurements at each of three heights in open and in forest.

Figure 107. Headquarters station. August 1, 1950.

anemometer, hygrothermograph, psychrometer, and maximum and minimum thermometers were operated for comparison and to provide continuity of record when any of the instruments at the West St. Louis Station were out of operation. In addition, daily readings of an 8-inch precipitation gage were recorded. Hygrothermograph, psychrometer, and maximum and minimum thermometers were also installed near the Fool Creek stream gage.

Sacramento-type seasonal storage precipitation gages were established at five locations within the basin as shown in figure 2. Snow measurements were made in the vicinity of each gage at the April 1, May 1, and June 1 visits of each year. A detailed presentation of the results of the observations with seasonal storage precipitation gages is given in section 5 of this report.

In the fall of 1939, a snow course approximately 3½ miles long was established in the Fool Creek watershed as is shown in figure 108. One hundred snow-sampling points were located at regular intervals along this course. Snow measurements were made at these points on April 1 and weekly or biweekly until the disappearance of snow. Early in 1940, clearings ranging from 50 to 100 feet in diameter were made at every other snow-sampling point, so that 50 snow samples were from

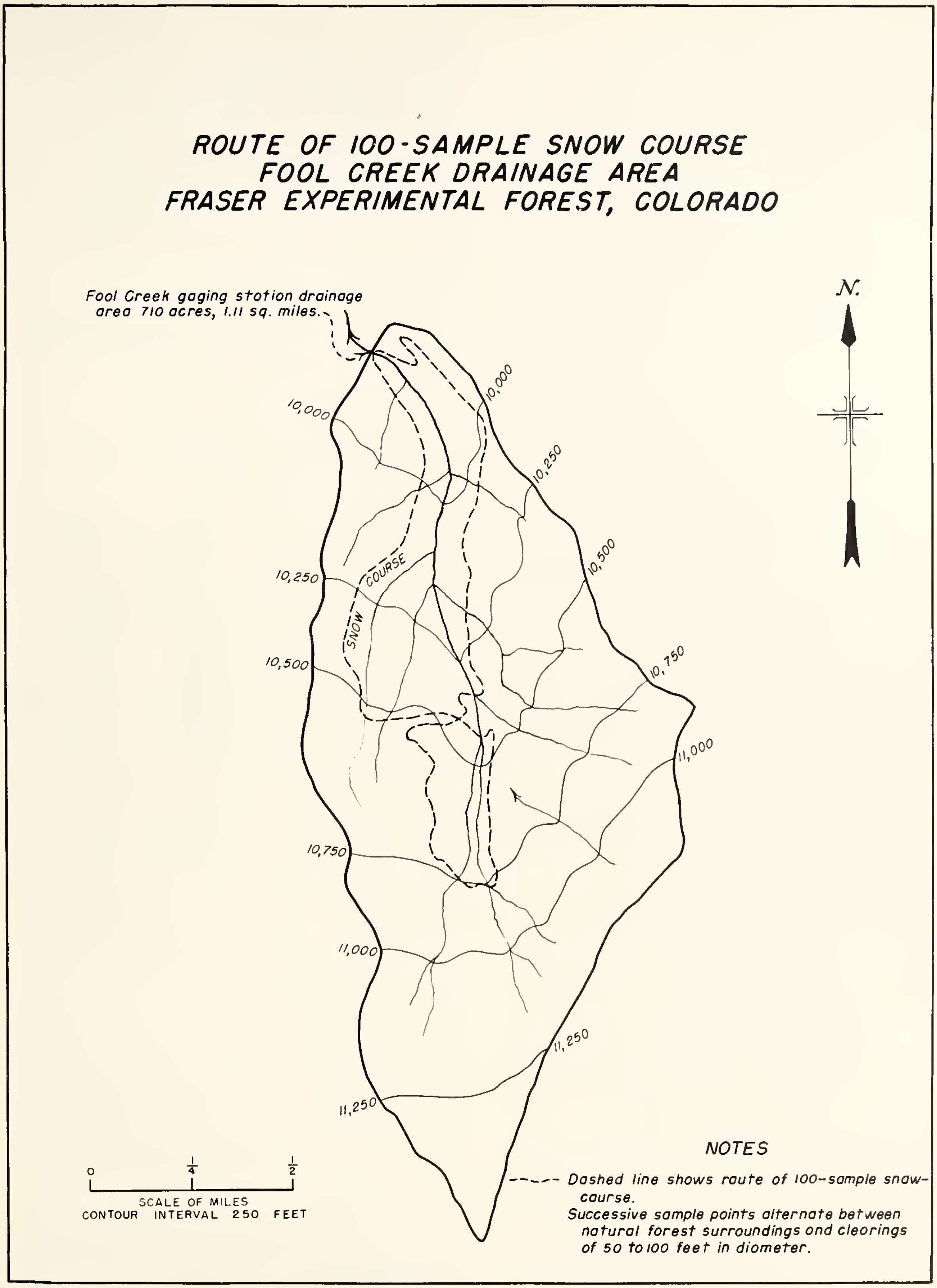

Figure 108. Route of 100-sample snow course in the Fool Creek drainage basin.

cleared areas and 50 from undisturbed forest areas.

During the summer of 1940, 15 standard 8-inch nonrecording rain gages were placed at equal intervals along the Fool Creek snow course. Readings were made semiweekly during the summers of 1940 and 1941. In early spring 1942, clearings ranging from 50 to 100 feet in diameter were made surrounding each gage. Subsequently, the gages were read weekly during the snowmelt seasons as well as during the summers. One recording precipitation gage was installed near the Fool Creek stream gage and was in operation during the summers from 1941 to 1953, inclusive.

In the East St. Louis Creek basin, the Forest Service established a 63-point snow course with the points in natural openings at about 200-foot intervals. The course was measured at the start of the snowmelt season each year from 1943 to 1953, inclusive. An 8-inch nonrecording rain gage near the East St. Louis Creek stream gage was read weekly during the snowmelt season during these same years. One recording gage at the same location was also operated during the summers from 1943 to 1953, inclusive.

Streamflow from the entire St. Louis Creek drainage basin was measured at the station operated jointly by the Geological Survey and the Colorado State Engineer. In addition, the Forest Service operated stream gages on Fool Creek and East St. Louis Creek.

A detailed description of each type of installation, together with a discussion of instrument characteristics and operation problems and improvements, follows:

A. Solar radiation measurements

The solar radiation station at Shadow Mountain Camp near Grand Lake, Colo., consisted of an Eppley ten-junction pyrheliometer, mounted about 25 feet above ground on top of a quonset-type building, and a recording potentiometer within the building. A record of solar and sky radiation incident upon a horizontal surface was obtained.

1. *Pyrheliometer.* The pyrheliometer was an Eppley ten-junction instrument of the Weather Bureau type. This instrument, which works on the thermocouple principle, is described in detail by Hand [51]. The responsive components of the pyrheliometer were mounted horizontally in the center of a thin spherical glass bulb, sealed to protect them. Specifications [51] require the instrument to have an output of between 1.5 and 2.0 millivolts per langley [9] per minute; a responsiveness of 55 seconds or less to develop maximum output due to a change of radiation from zero to one langley per minute; and a resistance of between 35 to 45 ohms. It should be sensitive to radiation of wave lengths between 0.295 and 2.5 microns (μ).[10] The lower limit is the limit of solar spectrum in the ultra-violet due to atmospheric absorption and the upper limit is the cutoff by the glass cover, which is practically opaque for wave lengths greater than 2.5μ.

The bulk of the radiation originating at the sun is between wave lengths 0.15 and 4μ, and the principal components of the radiation reaching the earth are [51]:

Ultraviolet, 0.29 to 0.4μ, 4 percent of total.
Visible, 0.4 to 0.7μ, 43 percent of total.
Infrared, longer than 0.7μ, 53 percent of total.

The percentages are approximate, since the position of the maximum of the solar energy curve varies with increasing air mass (length of the path through a homogeneous atmosphere over which the same attenuation would be produced as takes place in the actual path of the solar beam).

2. *Recording potentiometer.* The electromotive force (e. m. f.) produced by the impact of radiation upon the pyrheliometer was recorded on a strip chart recording potentiometer [63]. The recorder was operated at a chart speed of 1$^{35}/_{64}$ inches per hour. Auxiliary equipment included a heater, time switch, panel light, and standard cell protector. The recording potentiometer was powered by a dry cell whose voltage was balanced against the constant e. m. f. of a standard cell every 48 minutes.

To reduce the costs and the bulk of charts, the recording potentiometer was shut off overnight. There was, therefore, always a possibility that the standard cell would be in the circuit when the time switch shut off the recorder, thereby endangering the standard cell by allowing it to be in a circuit opposing the operating dry cell. Figure 109 shows the details of a standard cell protector and figure 110 is a wiring diagram showing how a mercury switch was incorporated in the circuit to protect the standard cell.

3. *Recorder chart and tabulation.* (a) *Typical chart.*—A typical record of one day's solar radia-

[9] 1 langley equals 1 gram calorie per square centimeter. 1 small or gram calorie equals 0.0039685 B. t. u.

[10] 1 micron equals 1/1,000,000 meter.

tion is shown in figure 111. The vertical scale on the recorder chart shows intensity of radiation with the smallest division representing 0.02 langley per minute. The spacing between vertical lines is 20 minutes of time. The time scale added at the bottom is Apparent Solar Time. Table 48 gives the corrections to be applied to Mountain Standard Time as of June 1950 to obtain Apparent Solar Time at Shadow Mountain Camp.

(b) *Obstructions.*—The sharp rise on the chart for October 14, 1950, in figure 111 at approximately 7:00 a. m. Apparent Solar Time occurred when the sun rose over the mountains in the east. Figure 112 shows graphically the position of the sun and all the permanent obstructions for this location. The mountains to the east, the telephone wires to the southwest, and the mountains and trees to the west all cut off some of the radiation. At the Fraser Experimental Forest, the position of the sun is practically identical as at Shadow Mountain Camp. The effect of mountains and trees on the horizon is, of course, different for each specific location. Clouds cut off much of the radiation and on heavily overcast days, the intensity of radiation received by the pyrheliometer is very low. When broken clouds pass over, the record shows a series of sharp vertical dips as in the afternoon of October 14, 1950. Often, between the dips caused by the obstruction of clouds, the record trace will be abnormally high due to the added radiation reflected from the nearby clouds. Notes were placed on the tabulation when this was obvious, but no attempt has been made to correct the charts for such conditions.

Corrections were made, however, for the effect of morning frost on the pyrheliometer bulb which served to refract and reflect radiation to the sensing element, causing markedly higher readings.

Table 48—Corrections to apply to Mountain Standard Time to obtain Solar Time at the Shadow Mountain Solar Radiation station

Shadow Mountain Solar Radiation Station near Grand Lake, Colo., longitude 105°51′ W, latitude 40°13′ N, elevation 8,417 feet.

Date		Corrections	Date		Corrections
January	1–3	−7	August	15–19	−7
	4–5	−8		20–23	−6
	6–7	−9		24–27	−5
	8–9	−10		28–30	−4
	10–12	−11		31–	−3
	13–15	−12	September	–2	−3
	16–18	−13		3–5	−2
	19–21	−14		6–8	−1
	22–25	−15		9–11	0
	26–30	−16		12–14	+1
	31–	−17		15–17	+2
February	–23	−17		18–20	+3
	24–28	−16		21–22	+4
March	1–5	−15		23–25	+5
	6–9	−14		26–28	+6
	10–13	−13		29–	+7
	14–17	−12	October	–1	+7
	18–20	−11		2–5	+8
	12–23	−10		6–8	+9
	24–27	−9		9–12	+10
	28–30	−8		13–16	+11
	31–	−7		17–22	+12
April	–2	−7		23–	+13
	3–6	−6	November	–14	+13
	7–9	−5		15–19	+12
	10–13	−4		20–23	+11
	14–17	−3		24–26	+10
	18–22	−2		27–29	+9
	23–27	−1		30–	+8
	28–	0	December	–2	+8
May	–6	0		3–4	+7
	7–21	+1		5–7	+6
	22–31	0		8–9	+5
June	1–6	−1		10–11	+4
	7–11	−2		12–13	+3
	12–16	−3		14–15	+2
	17–20	−4		16–17	+1
	21–25	−5		18–19	0
	26–30	−6		20–21	−1
July	1–5	−7		22–23	−2
	6–12	−8		24–25	−3
	13–	−9		26–27	−4
August	–8	−9		28–30	−5
	9–14	−8		31–	−6

Calculated by Solar Radiation Supervisory Station, United States Weather Bureau, Boston, Mass., and transmitted as enclosure to letter dated June 8, 1950, to R. K. Borene, Shadow Mountain Camp, Grand Lake, Colo.

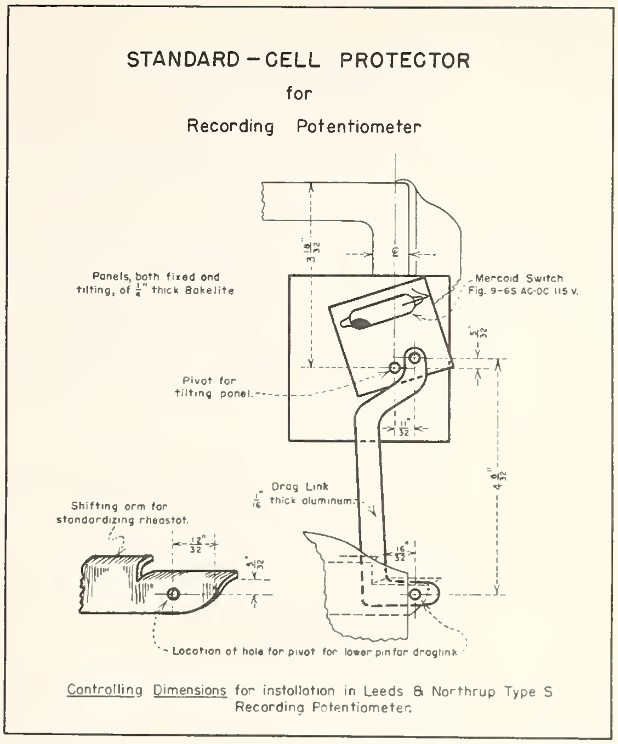

Figure 109. Standard-cell protector for recording potentiometer.

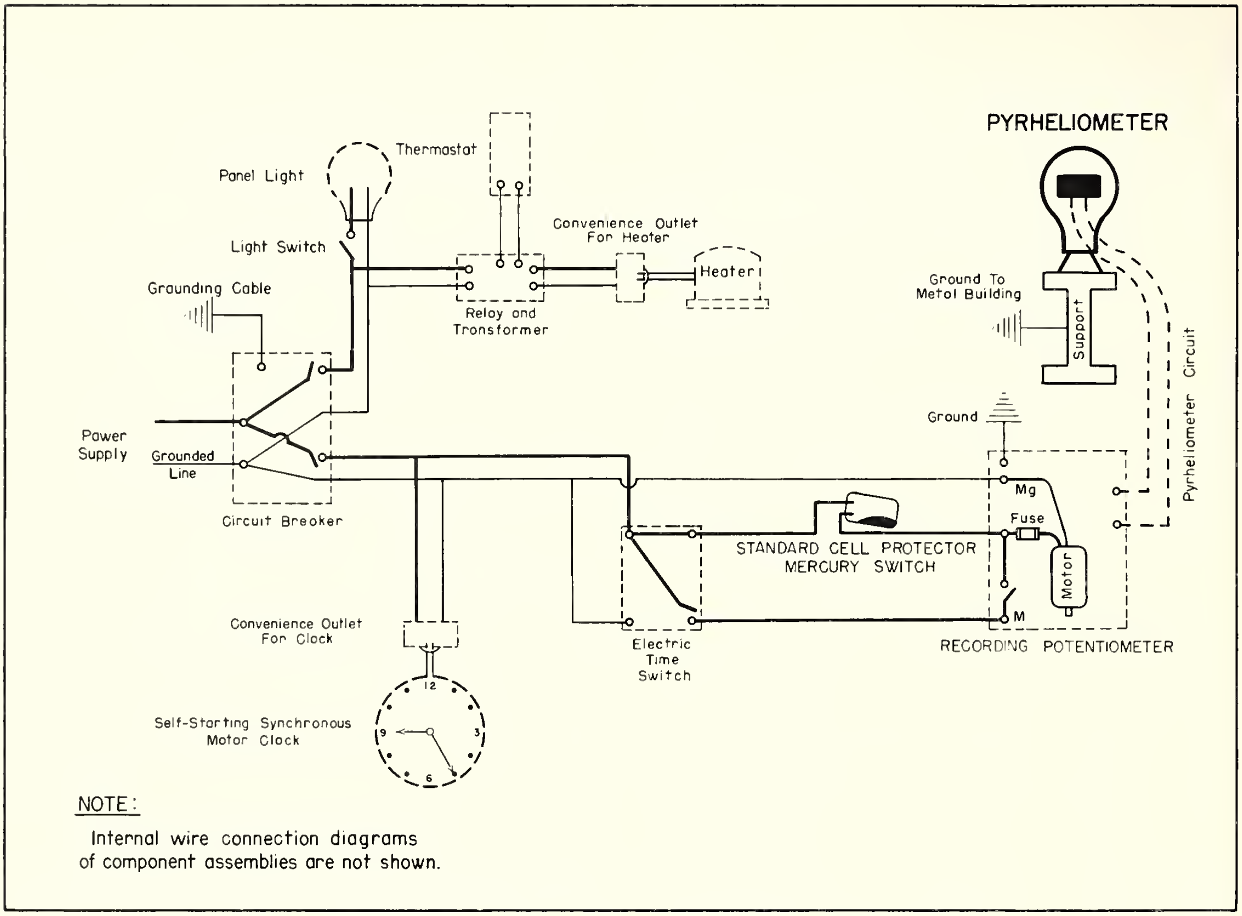

Figure 110. Wire-connection diagram for solar radiation station.

Whenever noticed, the frost was wiped off by the observer. The chart was corrected by comparison with an unaffected trace for the same time of year.

Hourly totals of radiation, daily totals, and weekly means were tabulated. Two auxiliary templates, a time scale and a grid overlay, used by the tabulator, were developed by the Processing and Analysis Unit of the Corps of Engineers-Weather Bureau Cooperative Snow Investigations, Oakland, Calif. [90].

The station pyrheliometer was calibrated periodically with a reference pyrheliometer which the Weather Bureau had standardized accurately on the Smithsonian Scale of Pyrheliometry. MacDonald and Foster [68] discussed the calibration of Eppley pyrheliometers, the fundamental standard pyrheliometer in the United States, the water flow pyrheliometer of the Smithsonian Institution, and the Ångstrom pyrheliometer, the European standard. MacDonald and Foster state that the two standards can be reconciled within 0.1 percent. The recording potentiometer was checked periodically for accuracy by an electronics engineer from the Weather Bureau.

Since pyrheliometric data are relatively rare, Hamon, Weiss, and Wilson [50] made an investigation of insolation as a function of daily sunshine duration. They developed empirical relationships between incident solar radiation received on the earth's surface and (1) percent of possible sunshine, (2) latitude, and (3) time of the year. These relationships were combined into a graphical method for converting percentage of possible sunshine into daily values of incident solar radiation for stations between latitudes 25° N. and 50° N. They tested the method on independent data from widely separated locations and obtained a correlation coefficient of 0.97 between estimated and observed values.

B. Wind measurements

1. *The installations.* Wind velocities were recorded at two windtowers in the drainage basin of West St. Louis Creek. The windtower in the

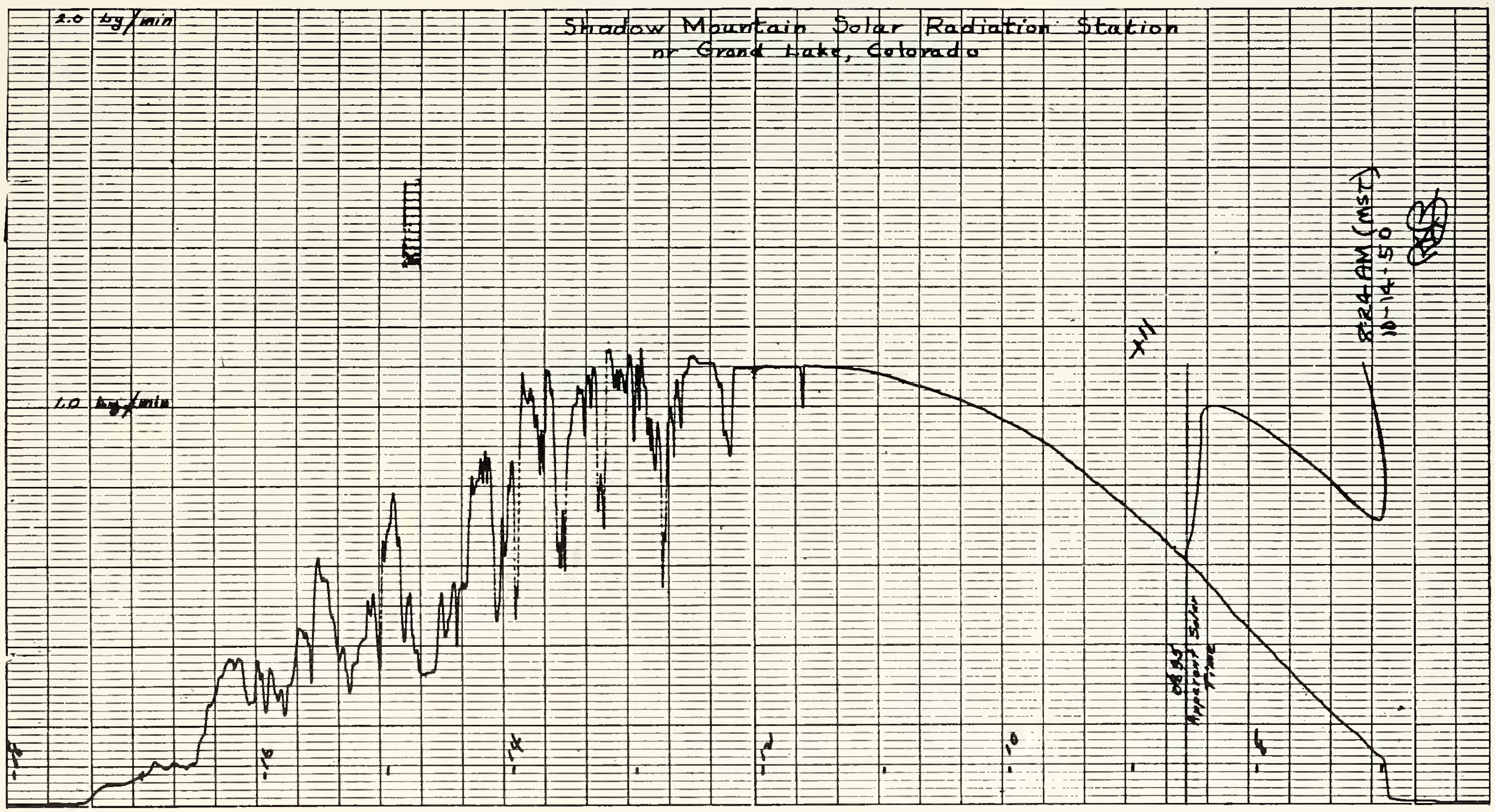

Figure 111. Chart recording of solar radiation for October 14, 1950.

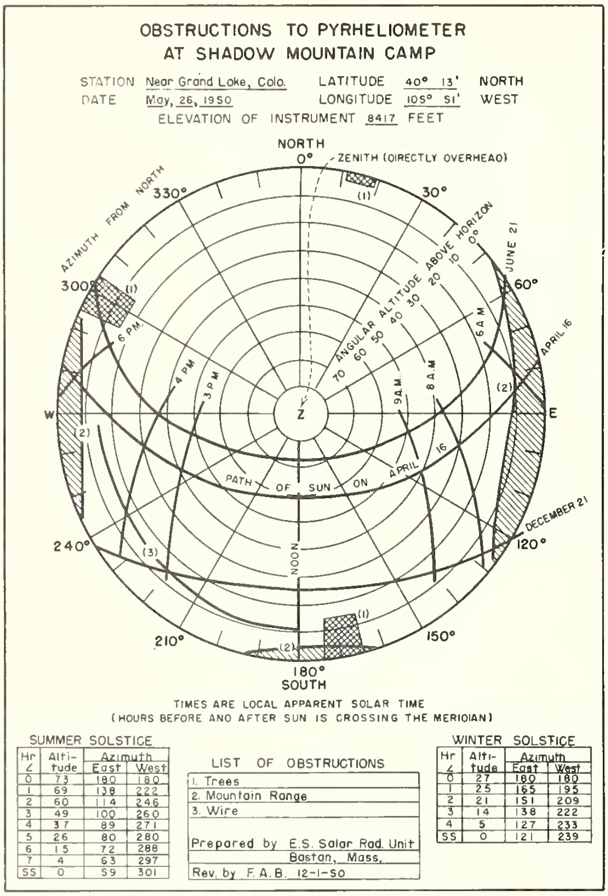

Figure 112. Obstructions to pyrheliometer at Shadow Mountain Camp.

open is shown in figure 106. Anemometers at this tower were operated at the following elevations of the cups:

Low—1.4 feet above snow or ground surface.
Medium—23.1 feet above ground surface.
High—47.4 feet above ground surface.

The low anemometer (figure 113), mounted on an adjustable bracket, was placed apart from the windtower and other structures, in order to expose it to wind not modified by impact upon nearby obstructions. In the forest, during the 1948 snowmelt season, two anemometers were installed on brackets affixed to living trees; cups were at the following elevations:

Low—1.4 feet above snow or forest floor.
Medium—22.5 feet above forest floor.

A steel lookout tower was erected in the forest in preparation for the 1949 snowmelt season (figure 114). This permitted the use in 1949 of three anemometers, which were installed at the following elevations:

Figure 113. Low-level anemometer at windtower in the open. October 24, 1947.

Figure 114. Looking up at middle and top anemometers on windtower in forest.

Low—1.4 feet above snow or forest floor.
Medium—24.9 feet above forest floor.
High—52.8 feet above forest floor.

2. *Anemometer.* Wind velocity and total wind increment measurements were made with cup anemometers which are described in the manu-

facturer's bulletin [13]. Cup arms and spindles are of stainless steel. The conical cups are of copper. Tests on stock models at the Bureau of Standards wind tunnel showed that this type of anemometer's registration was within 1 mile per hour of the true velocity throughout the range up to 100 miles per hour. No corrections were applied, therefore, to the anemometer records.

The anemometers used in this investigation were equipped with the standard 1-mile and 1/60-mile electrical contacts. In addition, total miles of wind passage were registered by each anemometer on an odometer. The mileages of total wind passage for specified periods of time, served as a check upon the performance of the remote registering wind recorder. The anemometers were cleaned and oiled at frequent intervals.

The effectiveness of the closure of the contacts was determined, for all positions of the contact wheel pins and cams, by determining contact circuit resistances with an indicating ohmmeter. The position of the movable contact arm was adjusted to just secure positive closure of the circuit on the shortest contact wheel pin or cam. Thereafter, periodic measurements of the resistance of open and closed circuit anemometer wiring installations in the field were made throughout the periods of record. Any departures from the normal values established for each circuit were investigated and suitable adjustments were made.

3. *Recording of wind velocity and direction.* All six anemometers at the two windtowers and one wind direction transmitting vane at the windtower in the open were recorded on one 20-pen, 108-ohm resistance, 12-volt-d. c. electromagnetically actuated, separate-circuit, operations recorder with hand-wound, spring-driven, chart drive. A chart speed of 3 inches per hour was found to provide adequate records of the wind velocities prevailing at the windtower site.

Recording 16 separate circuits placed a sufficiently heavy load on two automotive vehicle-type lead-acid storage batteries to discharge them in about one week's time. Battery power demands in such service are usually large, because anemometers tend to stop on contact when lulls in the wind occur, thus subjecting the batteries to continuing discharge for long periods. In order to protect against loss of records due to discharged batteries, and also to reduce the frequent replacement of discharged batteries with a set fully charged at Fraser, Colo., about 7 miles away, the simple d. c. recorder circuits were modified through the addition of capacitor and resistor components.

The introduction of capacitors and resistors modified the length of the effective electrical impulse reaching the 108-ohm resistance pen-actuating electromagnets. Steady rate discharge of batteries in anemometer circuits, such as would occur should the spindle stop on closed contacts, would then take place through a 4,700-ohm resistance, rather than through the 108-ohm electromagnets; but, for each cycle of opening and closing of contacts, the discharge from the 2,000-microfarad (μf.) capacitor would produce a surge of electrical energy sufficient to actuate the pen and produce a clear record.

A different modification was necessary to reduce battery power requirements of the wind direction recording circuits. A 135° included-angle cam on the wind vane shaft can close either one or two contacts at one time, thus making it possible to record wind direction from eight 45° sectors. With simple wiring, one or two circuits are closed at all times, thus causing continuing discharge through one or two recorder electromagnets. The wind vane circuit was modified through the introduction of a gas voltage regulator tube (No. 991), a capacitor, and a high resistance.

The 90-volt battery was active only in charging the capacitor. When a charge built up in the capacitor exceeding the breakdown potential of the gas voltage regulator tube, ionization of the gas momentarily converted the voltage regulator tube into a conductor, and permitted the capacitor to discharge. In doing so, the sensitive relay closed, momentarily energizing the 12-volt pen-electromagnet circuits. The closing of wind direction circuits by the cam on the wind vane merely served to distribute the impulse to the proper recording elements. The cycle was repeated about once every 108 seconds.

A characteristic of the regulator tube used is that, with age, it may respond to a lower voltage when exposed to light than when not so exposed. This trait was discovered and confirmed by electronic specialists when, after about three years of service, the recording system failed to work during night hours. When an annual replacement of the tube and 90-volt battery was initiated, no further failure of this sort was suffered.

The wind direction and velocity circuit modifications, made by C. R. Daum (see figures 115 and 116), were based upon circuits by Dr. L. J.

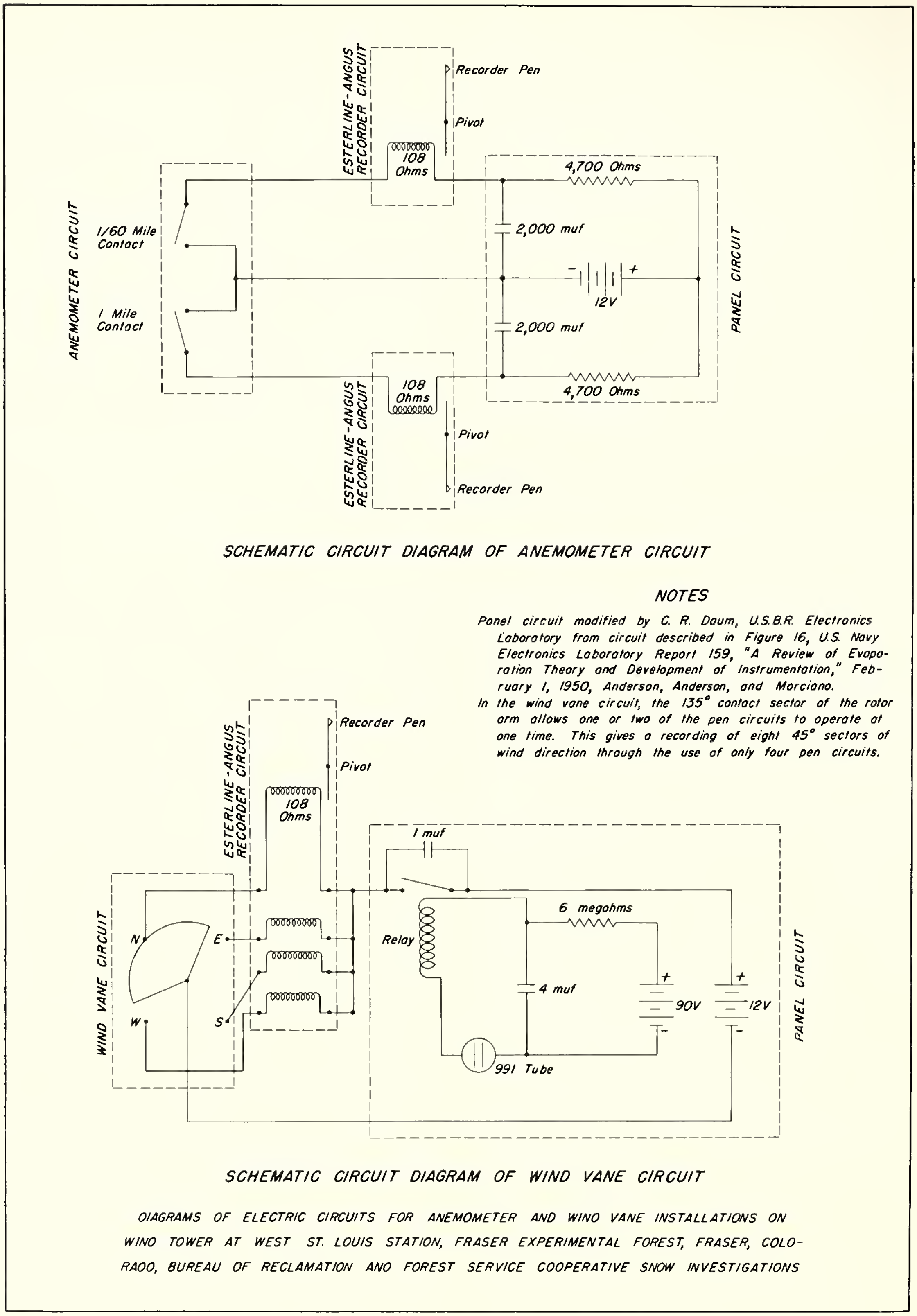

Figure 115. Schematic diagram of modified anemometer and wind vane circuits.

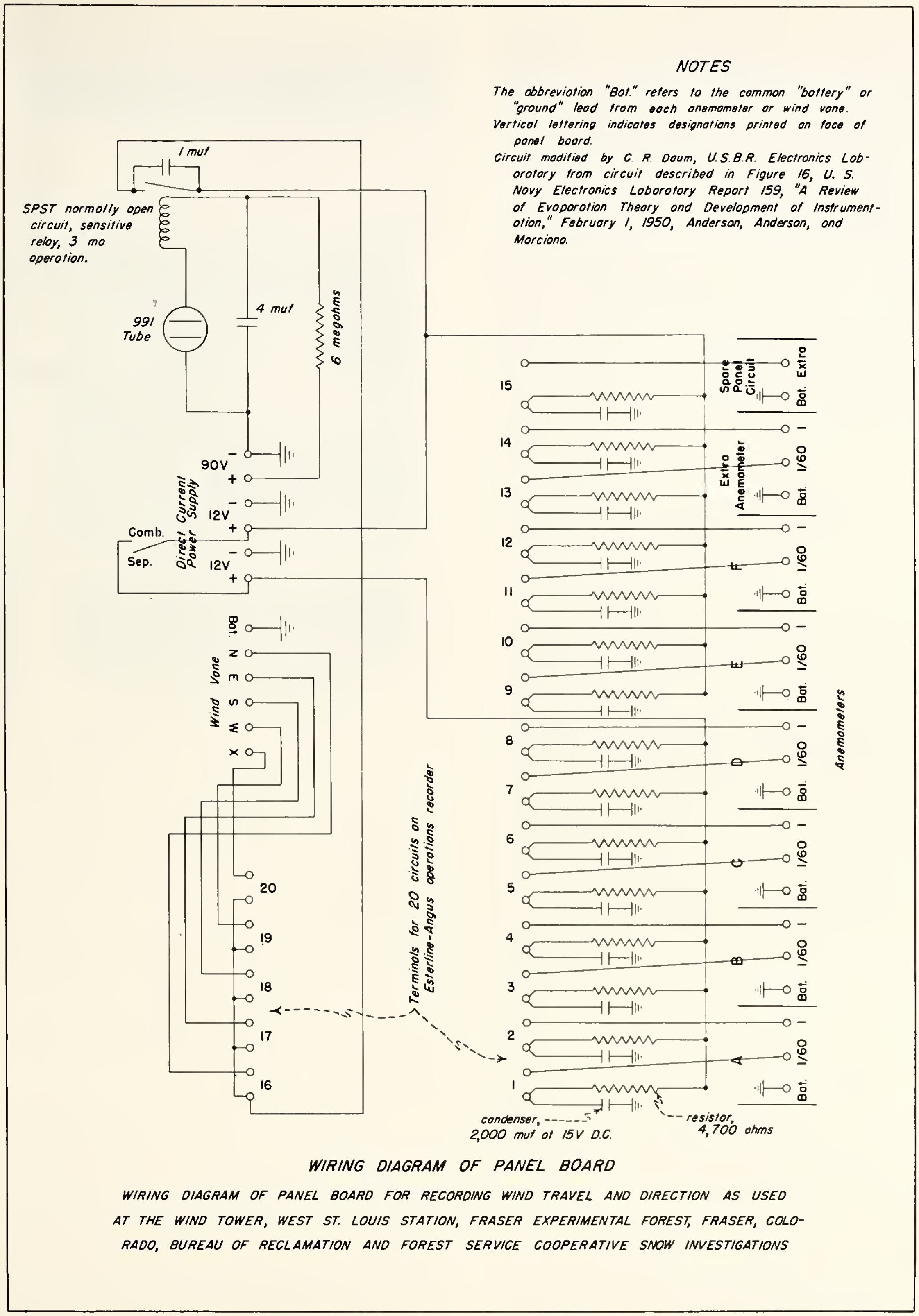

Figure 116. Wiring diagram of panel board.

Anderson of the U. S. Navy Electronics Laboratory [5].

The record produced by the modified circuits does not reproduce the long "pip," due to the inherent characteristics of the capacitor-discharge circuit. It was necessary, therefore, to make frequent checks of the completeness of the record. This was attained chiefly through comparison of the chart-recorded totals with the odometer increments, and, at times, by comparing the 1-mile and $\frac{1}{60}$-mile records from the same anemometer.

The operations recorder has a spring-driven, escapement-controlled chart feed. As it is very difficult, under field conditions, to adjust a clock to feed the chart exactly at the required number of inches per hour, it is usually necessary to make a time correction before records are transcribed from the chart. Correct time entries, inserted at frequent intervals on the margin of the chart, served as reference points for time corrections.

C. Temperature and humidity measurements

1. *The weather instrument shelter.* The instrument shelter used for the exposure of temperature and relative humidity measuring instruments was the standard large Weather Bureau shed-roof type, shown in figure 117. This shelter is sufficiently large to house a hygrothermograph, maximum and minimum thermometers, and a crank-type psychrometer. The shelter protects instruments against incident solar and sky radiation from above by a freely ventilated double roof. The shelters were installed upon solidly anchored timber or log supports with the door facing the north, to prevent direct impact of solar radiation upon the instruments when the door is opened for reading or servicing the instruments.

2. *Thermometers.* Standard Weather Bureau maximum and minimum thermometers were mounted on Townsend-type supports shown in figure 117. The minimum thermometer rests at the proper angle to assist in the depression of the "rider" in the capillary tube upon falling temperatures, but to resist upward movement of the "rider" upon rising temperatures. Provision is made for rotation of the thermometer to bring the "rider" to the temperature current at the time of servicing. The maximum thermometer clamp is free to rotate upon release of a positioning latch. Spinning the maximum thermometer at the time of servicing exerts a centrifugal force which returns the mercury from the capillary tube into the bulb until the current temperature is reached.

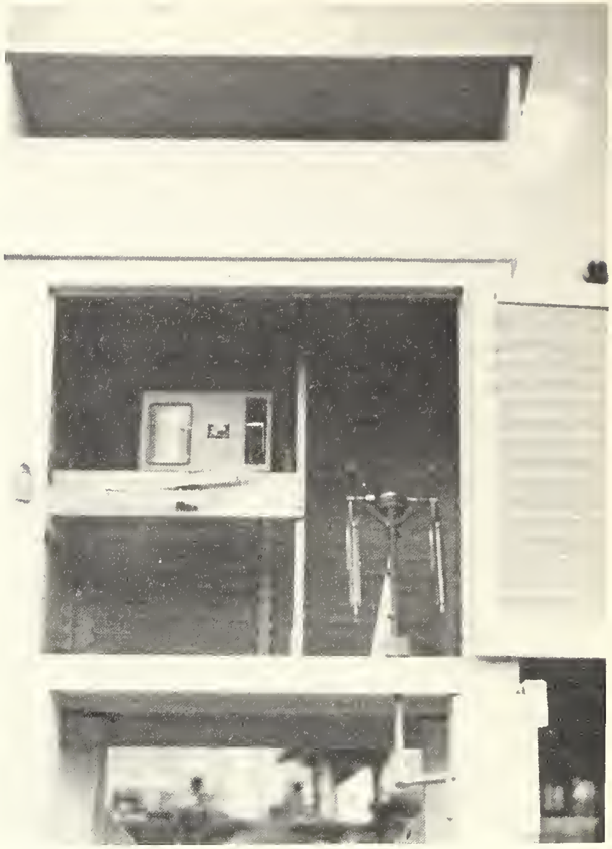

Figure 117. Interior of weather shelter at Shadow Mountain Camp. June 8, 1948.

3. *Crank-type psychrometer.* A crank-type psychrometer was used for concurrent wet and dry bulb readings. The instrument shown in figure 117 was built in the shops of the Division of Engineering Laboratories, Bureau of Reclamation, Denver, Colo., and patterned after the Standard Weather Bureau design. This manner of rotating wet- and dry-bulb thermometers offers several advantages when used on snowmelt investigations:

(a) It permits spinning the thermometers in the shade of the instrument shelter without exposure to direct sunlight.

(b) The gear drive produces high velocities of motion through the air without the need of electrical power supply such as is needed for motor-driven air aspirators.

(c) This psychrometer makes it easy to spin the thermometers for the long periods of time required to attain the true depression of the wet bulb at air temperatures below 32° F.

The thermometers used in the crank-type psychrometers were matched sets which conformed to Weather Bureau standards for psychrometric pairs. The wet-bulb cloth socks were replaced with new ones as soon as they became visibly stained. Distilled water was used to wet the socks at the time of a psychrometric reading.

4. *Hygrothermograph.* Continuous records of air temperature and of relative humidity were obtained by hygrothermographs.

(a) *Temperature recording system.*—The temperature element is a liquid-filled Bourdon tube, one end of which is attached to a hinged arm which permits adjustment of pen position and changes of the temperature indicating range. The movement of the pen spans a range greater than 100° F. The temperature recording system is accurate within 1° F. within the entire range of 100° F. The hinged support permits selection of temperature indication designations on the chart to include seasonal ranges. The lever system contains provision for adjustment of lever-arm motions to translate the movement of the Bourdon tube into movement of the pen to conform to the printed chart scale. As the temperature recording system is mechanically actuated, before a record of a change in temperature is produced, a sufficiently large change in the volume of the liquid in the Bourdon tube must take place to exert forces large enough to overcome the resistance to change of shape of the Bourdon element, pivot friction in the lever system, and pen drag on the chart. It is evident, therefore, that the temperature recorder is relatively insensitive to small and rapid fluctuation of air temperature and that exact agreement is seldom attained between the chart-recorded and thermometer-indicated maxima and minima.

Calibration adjustments to the lever-arm ratio, if necessary, can be made only with the aid of accurately controlled temperature chambers. Figure 118 shows a modification to the lever arm of the mechanism transmitting movements of the Bourdon tube to the recording pen. The originally cylindrical rod attached to the shaft which also carries the pen arm and to which the drag-link from the Bourdon was connected, was modified by threading it. The two nuts make possible micrometric positioning of the arm for accurate calibration adjustment of the temperature recording system.

Orientation of the pen position on the chart is

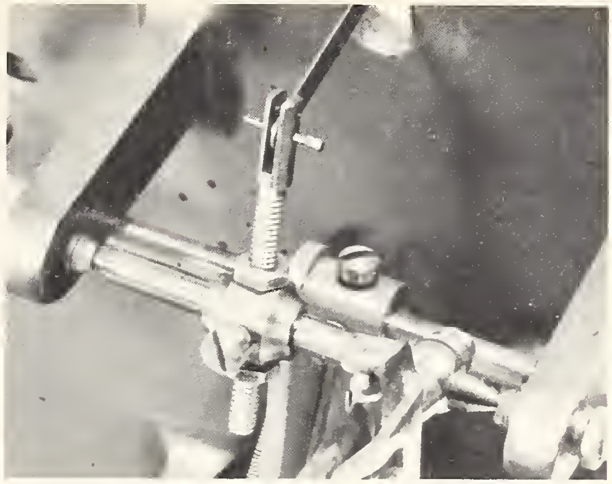

Figure 118. Modification of the lever arm mechanism of the temperature recording system. The Bourdon tube is connected to the far end of the pinned drag link beyond the hole in the case, and the pen arm projects into the foreground. The threaded rod which translates movement of the Bourdon tube to the pen arm permits micrometric adjustments to the lever-arm ratio.

made by repositioning the hinged arm holding the Bourdon tube, through moving of the milled nut on the hinge anchor bolt.

(b) *Humidity recording system.*—Measurement and recording of the water vapor of air over a snowfield is extremely difficult. The water vapor content of the air is usually derived indirectly from measurements of dewpoint or of relative humidity. Probably the most satisfactory method now available is the dewpoint recorder method, recent improvements of which are described by Barrett and Herndon [10]. However, this method was not considered applicable to the field installations of the cooperative snow investigations because of the delicacy of its component parts, its demands for electrical energy and refrigerants, and because of its high cost. Instead, the human-hair type of hygrograph was chosen for this program because of its relative simplicity and lower cost. The relative humidity recording system of the hygrothermograph consists of a hair sensing element, a lever system (including rocker arms), and the pen.

The hair element consists of twelve clusters of about four human hairs each, affixed in banjo-string fashion to brass clamping plates. The use of human hair is based upon its characteristic of changing length in response to changes of relative humidity of the air over a considerable range of

air temperatures and water vapor pressures. Only hairs in a natural condition possess this characteristic since hair that has been modified by the application of heat or subjected to chemical changes loses sensitivity and responsiveness to change in relative humidity of the air. Hair suitable for use in hygrographs is treated with ethyl ether for one hour to extract fats as the presence of fats or oils on hair elements is very undesirable. The changes in length of human hair in response to relative humidity changes are practically logarithmic between relative humidities of 20 to 100 percent. The rocker arms in the lever system serve to convert this exponential response to linear movement of the pen. Detailed discussions of the human-hair hygrometers are given by Middleton [70] and Mueller [74].

It has been observed that different hair elements change their lengths different amounts in response to identical relative humidity changes. This necessitates adjustment of the lever arm ratios to change the degree of magnification of the lever system to retain a standardized pen travel on printed recorder charts. It was found that the recorder lever system is very sensitive to changes in the main lever arm ratios. Great difficulty was experienced in clamping the lever arm as the cup-shaped end of the set screws tended to deform the surface of the main lever arm to a crater into which the set screw would clamp. Accordingly, the main lever arm was improved by incorporating a micrometric adjustment, as shown on figure 119.

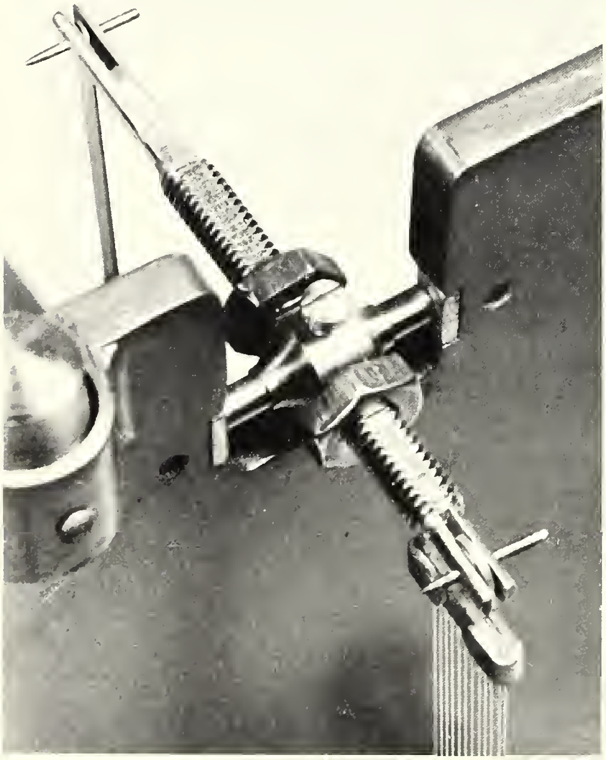

Figure 119. Modification to humidity-recording system. Lever connecting hair element in foreground to drag link to rocker arms has been threaded and nuts added to permit micrometric calibration adjustments in the lever-arm ratio.

A change in the position of the fulcrum of the main lever arm of $\frac{1}{20}$ inch changed, for a difference of 45-percent relative humidity, the chart span of the pen from 45 to 39 percent. This means that a change in the position of the fulcrum of $\frac{1}{20}$ inch changes the total span (0 to 100 percent) of the pen travel on the chart by 2-percent indicated relative humidity. The use of the micrometric lever arm adjustment made it possible to return exactly to a previously tested position of the fulcrum.

It was observed in a number of instruments that excessive time lags were evident in the charts. In certain instances, this was found to be caused by too close a mounting of the rocker arm contact-retaining spring, so that, at certain positions of the rocker arms, the spring would rub against the arm and impede movements of the pen arm. This difficulty was removed by cutting new spring retainer grooves in the pins on the rocker arms, as shown in figure 120.

Another source of trouble may be due to inaccurate positioning of the rocker arms with ref-

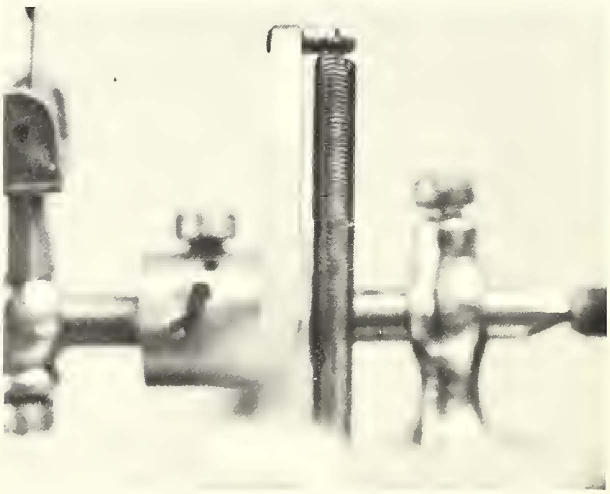

Figure 120. Lower rocker arm and pen shaft of hygrograph showing repositioned tension spring attachment.

erence to each other, as a result either of inaccurate attachment to the shafts or to misalignment of the shafts. The rocker arms should be positioned so that their contact is along the crests of the curved surfaces. Inaccurate positioning of the lever-system components may cause loss of part of the record when the end of the lower rocker arm contacts the vertical chassis. This can be corrected by proper clamping of the various levers to the shafts in regard to the angular travel which each lever must perform, so that rocker arms contact each other near the center of their arcs when the pen rests at 50-percent relative humidity on the chart.

It was observed that hygrothermographs in the best possible calibration tended to behave erratically after shipment and installation in the field. In order to make certain that there would be no mechanical stretching of the hair element with resultant loss of calibration, the hair element releasing bolt, as shown in figure 121, was developed. When the bolt is in its down position, closing of the cover of the hygrothermograph automatically releases the hair element, thus protecting the hairs against loss of calibration due to stretching to which they might be subjected in shipment and handling.

(c) *Sensitivity of the humidity element.*—The human-hair humidity element is relatively insensitive to rapid fluctuations in relative humidity. This slow responsiveness is further damped by the pivot friction and pen drag of the recording mechanism. Before a record is produced of a change in relative humidity, a sufficient change must result in the amount of water adsorbed on the hair to produce enough change in length of the element to exert enough force to overcome pivot friction and pen drag, and move the pen. Inherent accuracy of the human-hair hygrometer is generally accepted as ± 3-percent relative humidity and its sensitivity as ± 1-percent relative humidity in the range between 20- and 95-percent relative humidity at air temperatures above freezing. At lower temperatures, possible freezing of the adsorbed water on some hairs may cause abrupt changes in lengths not indicative of changes in relative humidity. At temperatures considerably below freezing, when water vapor pressures become very low, the hair element's response tends to be more and more completely

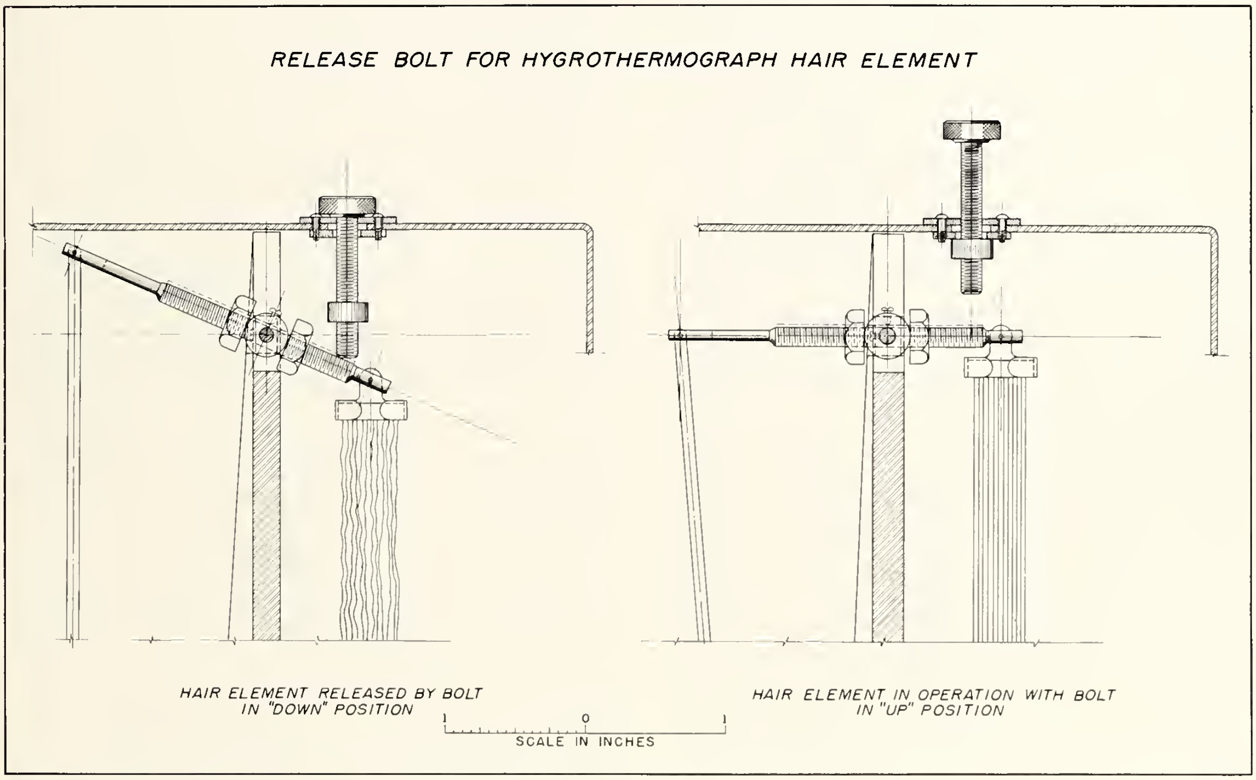

Figure 121. Release bolt for hygrothermograph hair element.

dominated by temperatures, the lag becoming almost infinite at −40° C. According to Middleton [70], the change in length of human hair is about 1/15 as much per degree C as is the mean change in length for a change of 1-percent relative humidity.

It is evident, therefore, that the recorded relative humidity can only rarely indicate the true relative humidity at the instant of observation. For this reason, exact accord between relative humidity recorded on the chart and relative humidity determined by the wet- and dry-bulb psychrometer is seldom observed. As this lag is operative upon both increasing and decreasing relative humidities, the hygrograph produces a record which acceptably reflects the changes in relative humidity which occurred over the period recorded. Discrepancies as large as 30 percent may be noted between chart-recorded and psychrometer-measured concurrent relative humidity for a hygrothermograph in the best possible adjustment. A comparison between such readings for the Shadow Mountain Station is shown in figure 105. It is evident that the hair element of a hygrograph cannot be calibrated with reference to a few psychrometric determinations performed in the field.

(d) *Calibration.* — The hygrothermographs used in the cooperative snow investigations were calibrated in the controlled temperature and relative-humidity rooms of the Division of Engineering Laboratories, Bureau of Reclamation, Denver Federal Center, Denver, Colo. Controlled temperature chambers maintained at temperatures varying from −30° F. to +220° F. are available. Two chambers were used for humidity element calibration:

(1) 73.4° F—50-percent relative humidity.
(2) 73.4° F—100-percent relative humidity (fog room).

The humidity in the 73.4° F 50-percent relative humidity room is controlled through the use of the Dunmore sensing element [35]. The temperature and humidity controls used are described in Reference 4. The installation is capable of maintaining the relative humidity within the room to within ±1.5 percent of that desired, with a sensitivity of 0.5 percent.

Fog conditions are maintained in the 73.4° F fog room through a continuous spraying of water from specially designed nozzles. Hair elements were calibrated in these two chambers and no attempt was made in the field to adjust the relative humidity pens to agree with wet- and dry-bulb psychrometric measurements. It was found that replacement of the hair elements required readjustment of the main lever arm ratio, which could be performed only in the controlled-temperature and relative-humidity chambers.

Facilities such as those in the Bureau of Reclamation's Division of Engineering Laboratories are unique. However, humidity element calibration in the field may be done in small sealed chambers within which known relative humidities can be produced through the exposure of trays of saturated aqueous solutions of certain salts. For example, sodium chloride, NaCl, at 40° C produces in the closed chamber a relative humidity of 74.7 percent. Detailed information on this subject is given by Carr [19] and Stokes [82].

(e) *Suggestions for operating hygrothermographs.*—As records of temperature and relative humidity are important in snowmelt investigations, since they are components of Light's equation and both simple and multiple correlation analyses, special attention was paid to the operational techniques of maintaining a hygrothermograph. Experience and observations made during the conduct of these cooperative investigations suggest the following precautions and operational instructions:

(1) *Exposure.* A hygrothermograph should be installed in a shelter that allows free ventilation, but at the same time restricts the entry of blowing snow. It should be mounted on a shelf, and off the floor of the shelter, to allow air circulation all around the hygrothermograph. The shelter should also shade the instrument from solar and sky radiation, and have a ventilated roof to prevent the interior of the shelter from heating up due to the solar heat absorbed by the roof. The Weather Bureau large instrument shelters are considered standard, although even they will fill up with blown snow in windy exposures. The small so-called "Cotton Region" shelters, which were designed for use of maximum and minimum thermometers, are not desirable for the exposure of hygrothermographs.

(2) *Care in handling.* Because of the sensitivity and delicacy of the sensing elements in the hygrothermographs, the instruments should be handled with extreme care. No jars or strains should be transmitted to either the Bourdon tube

or to the hair element. The hairs should not be touched, because oil from the hand will change their responsiveness and the slightest snag may stretch the hairs.

(3) *Preparation for shipping.* Before transporting the hygrothermograph long distances, the following precautions should be taken. If the instrument does not have a hair element release bolt, the hairs should be slackened by looping a fine wire through the slit in the lever arm and twisting its around the adjusting nut, thus holding the hairs in a loose position. When thus tied down, no vibration or tension can be placed on the hair element in shipment. The main lever arm should be pulled down far enough to put the hairs into a definite slack, but not so far as to cause the other end of the lever arm to touch the hinged cover. Both hydrograph pen and thermograph pen should be tied loosely to the upright pen releasing arm to prevent vibration, but not to prevent normal movement of the thermograph pen in response to changes in temperature in shipment. The hold-down clip used to retain the charts on the clock drum should be taped to the inside floor of the instrument to prevent loss or bending. The clock should be removed and wrapped separately to exclude dust.

(4) *Inking and cleaning pens.* The cork of the ink bottle supplied for use with the instrument has a flat-bladed ink dipper which is used to add ink to pens. Periodically, the pens should be cleaned by pulling this blade through the pen point between the nibs. Periodic washing in 99-percent ethyl alcohol may be required when instruments are operated under dusty conditions.

(5) *Par-timing of pens.* It is important when using the hygrothermograph records for computation of dew-points that the two pens register on the same time line of the chart at any one instant. The pens are fastened to the pen arms with sliding friction grips and can be slid on the pen arms until the two pens agree. Normally, this is done when the instrument is calibrated, but in addition, th par-timing should be checked periodically. When sliding the pen on the pen arms, the pen arm should be held firmly against the upright pen releasing arm so that no strain will be put on the sensing elements. The humidity pen arm should first be lowered slightly to relieve tension in the hairs.

(6) *Putting chart on drum.* The charts have a 7/8-inch tab at each end of the chart grid. The tab at the left end has the identifying number and the tab at the right end has space for pertinent remarks, instrument number, station, and date. Before wrapping chart around the drum, the tab with the notes is folded under. The chart is wrapped on the drum so that the folded end is lapped over the unfolded end and the fold is just past the slot in the flange at the bottom of the drum. The chart clip is inserted within the folded end and its end is engaged in the slot in the flange. The clock then rotates so that the pen will ride up on the paper over the chart clip without catching. If the wrong end of the chart is folded under, the pen point will catch on the fold around the chart clip and the clock movement may either pull the pens off the pen arms or the pens may stop the drum. Care should be taken to see that the chart rests squarely against the bottom flange. The chart can be snugged up on the drum by rubbing with the hands to slide the unfolded tab under the chart clip. Care should be taken that the horizontal lines on the chart match where the two ends meet. This can be checked by sighting along the lines across the joint.

(7) *Starting clock.* Because of the slack in the clock gears the starting time of the pen trace will not agree with the printed grid unless the slack is taken up in the proper direction. To take up the slack, the clock is rotated counter-clockwise until gears are tight before setting pen on time line. When released, the clock may rotate slightly clockwise and then remain stationary until moving gears have again taken up the slack.

(8) *Changing temperature range.* The summer charts have a temperature range from 10° F. to 110° F. and the winter charts range from −30° F. to 70° F. The range can be set to span lower temperatures, provided that proper notation of the effective range is entered on each chart. Changing from one range chart to another is done when the temperature is fairly constant. The chart reading of the pen trace is observed on the old chart before removing it. The new chart is put on and the pen moved to proper reading by turning the adjusting screw at the end of the case near the Bourdon tube. Turning the screw to the right will lower the pen and turning the screw to the left will raise the pen. The new setting should be checked with a thermometer.

(9) *Time checks.* As often as is practical, time

checks should be made on the hygrothermograph charts. The time can be noted on the trace by a small "pip" of the pen. To make this "pip", move the pen very slightly with the end of a pencil. Just the weight of the pencil is usually sufficient to move the pen enough to make a visible "pip".

(10) *Notes.* Adequate notes should be kept on the chart. Time of starting and ending and any intermediate time checks should be included. Temperature and psychrometer checks should be noted when read. All notes can be written on the chart in the field. When writing on the chart, first note the correct time and then remove the clock from the instrument. Makes notes on the chart while it is still on the clock drum. The clock should be replaced to the proper time setting.

The significance, in terms of accuracy of forecasting runoff from snowmelt, of careful operation and maintenance of properly calibrated hygrothermographs is brought out in section 13.

D. Precipitation measurements

1. *Sacramento-type storage gages.* The Sacramento-type storage gages used are 100-inch and 200-inch-capacity gages similar to those described by Codd [25] and were fabricated by the Bureau of Reclamation's Division of Engineering Laboratories from Weather Bureau plans as described by Gerdel [46]. The gage is in the shape of a truncated cone with an 8-inch-diameter opening at the top. It is mounted on supports above the level of the maximum accumulation of snow as shown in figure 122. Wind shields of the Alter type were fastened to the gages to control air currents which might deflect falling snow away from the opening. The wind shield consists of a fence of slats hung from a circular frame around the opening. The bottoms of the slats are restrained loosely by a chain so that they are free to move slightly in the wind and dislodge any accumulated snow.

(a) *Antifreeze solution.*—At the start of the snow season, the gages were charged with a concentrated antifreeze solution. Amount of charge used is about 1 to 1½ times as much as the accumulation of precipitation to be expected in one season. Instructions given by the Weather Bureau [95] were followed when preparing the antifreeze charges. This reference recommends using a 29.6-percent solution of calcium chloride for the charge

Figure 122. Sacramento-type seasonal storage gage at the Iron Creek site. November 1946.

which has a freezing point of −59.8° F. Since the calcium chloride brine is very corrosive, the interior of the gage was coated with a bituminous paint. The exterior of the gage was painted flat black to increase absorption of solar heat.

The substances used in seasonal storage precipitation gages as antifreeze are chiefly calcium chloride or ethylene glycol, the latter usually in commercial form as antifreeze preparation for use in the cooling systems of automotive vehicles. Reference 96 discusses in detail the preparation of calcium chloride solutions and the initial charges to be used and charges for replenishment of various types of storage precipitation gages.

Although calcium chloride is exceptionally effective in depressing the freezing point in aqueous solutions, much trouble has been experienced in the field with calcium chloride charges. This trouble has resulted chiefly from the fact that the calcium chloride in solution forms several hydrates. As the amount of calcium chloride is increased above a concentration of 29.6 percent by weight, the freezing point goes up so that at about 35-percent

calcium chloride by weight, the depression of the freezing point is only to about 22° F above zero. The replenishment of concentration of calcium chloride in precipitation gages should be attempted, therefore, with caution. As the incoming precipitation catchments dilute the calcium chloride, raising its freezing point, replenishment of the chloride concentration should be only done by first dissolving the booster charge in water, then adding it to the rain gage and stirring thoroughly. If calcium chloride in solid form is added to a rain gage, it often produces a heavy hydrate which results practically in loss of protection against freezing.

Freezing point depression for calcium chloride and ethylene glycol solutions is shown in figure 123, which is based on data from Cragoe [27],

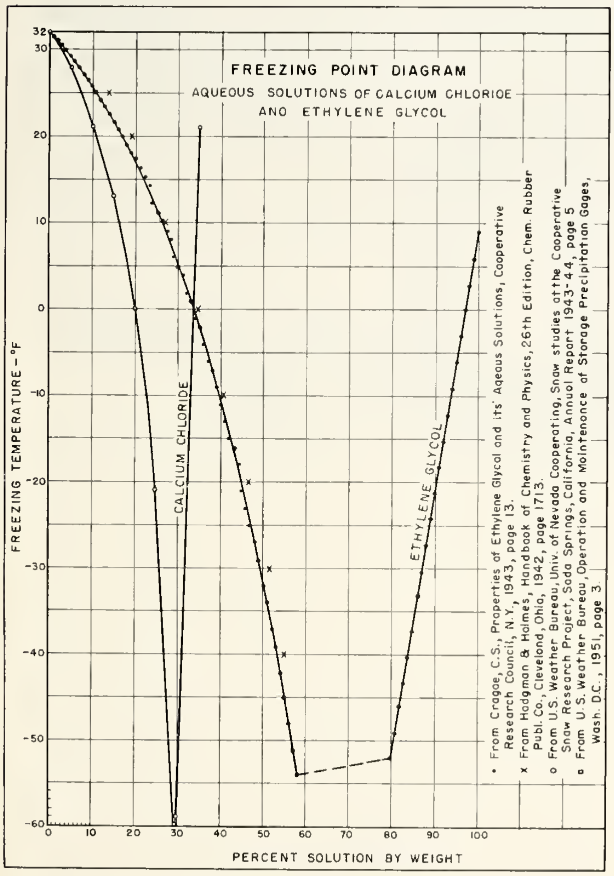

Figure 123. Freezing point diagrams for calcium chloride and ethylene glycol solutions.

Hodgman and Holmes [54], Gerdel [46], and the Weather Bureau [96]. The curve for ethylene glycol is especially interesting. Pure ethylene glycol has a flashpoint of 245° F, and therefore, its use would create a definite fire hazard. However, solutions having less than 85-percent ethylene glycol, by weight, do not constitute a fire hazard. The commercially-prepared ethylene glycol antifreezes for use in automotive radiators consist of an ethylene glycol base combined with various inhibitor ingredients to prevent foaming, creeping, rust loosening, and corrosion. The usual effect of the incorporation of these ingredients is to increase the freezing point depression effectiveness of the ethylene glycol solution, although this differs with substances used by the various manufacturers of radiator antifreeze compounds. Undercooling and viscosity make accurate freezing point determinations of ethylene glycol solutions below −75° F very difficult, but extrapolations of the curve indicate a maximum freezing point depression to −92° F, according to Church [20].

(b) *Antievaporants.*—Antifreeze compounds in precipitation storage gages are used not simply to protect the gage itself against disruption when the catchment freezes, but also to absorb snowfall and hold it in liquid condition in the antifreeze solution under the protection of a layer of oil, preventing evaporation loss. Various quantities of different kinds of oils have been used for this purpose. Usually, SAE–10 motor lubricating oil is employed. When a thin film of automotive lubricating oil is exposed to the air for a long period of time, various impurities, dust, and substances brought down by the precipitation tend to convert the oil layer into a leatherlike film which resists the penetration of incoming precipitation. The observation of an accumulation of snowfall in storage gages resting on top of the layer of oil is not unusual. Obviously, such separation of the most recent storm's contribution from the previous catchments leads to errors in the precipitation gage records.

It would be reasonable to presume that the data to be yielded by precipitation storage gages for a winter during which no snowmelt has occurred should be greater than that reported by the snow surveys in the vicinity of the gage, since, assuming 100-percent effectiveness of the installation, the catchment in the gage should hold all that fell, whereas the snow pack has been subjected to a possibly small amount of melting at the bottom of the pack in early winter and due to evaporation losses from the surface of the snow pack throughout the winter. However, precipitation storage gage

catchments equaling snow-water equivalents of a snow course are very rare.

A laboratory investigation conducted by the Bureau of Reclamation showed that ion-free transformer oil was the best of many substances used to reduce evaporation from precipitation gages.

Hamilton and Andrews [49] reported upon their independently conducted investigation performed by the Forest Service in southern California that they likewise concluded that transformer oil was best. Transformer oil is being used in the rain gages in the Fraser Experimental Forest and also in the radio-reporting network in the Sacramento River Basin described in Reference 87.

Figure 124. Weighing an 8-inch precipitation gage at West St. Louis Station, April 1950.

(c) *Calibration.*—The gages were measured by reading the depth of fluid with a stick lowered into the gage from the top. The depths were converted to volume by reference to calibration curves. These curves were derived for each gage by the Division of Engineering Laboratories, Bureau of Reclamation, by adding known increments of water to the initial charge of brine, and getting the corresponding depth readings.

(d) *Method of operation.*—On or about October 1 of each year, the gages were charged with a known weight of calcium chloride solution and oil. Stick readings were taken and the charging volume calculated from the calibration curve. On April 1 next, stick readings were again taken and the total volume computed. The difference of these two volumes was the increment of precipitation that was caught by the gage during the winter. Readings were taken again on May 1, June 1, and about October 1. At this last date the gage was drained into measuring pails and the solution was weighed as a check on the stick readings.

2. *Intensity gages.* The recording precipitation gages are Friez Universal Recording Rain and Snow Gages, one of which is shown in figure 107. They operate on the principal of weight transmitted through a series of linkages to record precipitation directly on a chart in inches depth. Precipitation is received in a bucket through an 8-inch-diameter opening. The chart is held on a clock-driven drum which rotates once each week. The resulting record gives the depth of precipitation and the time and intensity at which it fell for each storm. The gages have capacity for 12 inches of precipitation.

3. *Eight-inch nonrecording gage.* The 8-inch storage gage cans are similar to the Weather Bureau standard 8-inch precipitation gages. During the snowmelt season they were charged with a calcium chloride and oil solution. Readings were made weekly by weighing the can and contents as shown in figure 124. Increments in weight between weekly weighings were converted to inches of precipitation by using the conversion factor for 8-inch cans:

1 pound water = 0.55-inch depth.

The cans at the Headquarters and West St. Louis Stations were equipped with the Alter-type wind shields while the cans in the Fool Creek and East St. Louis Creek areas were unshielded.

E. Snow measurements

Snow surveys are performed with the Federal Snow Sampler, which is described by Marr [69]. Essentially, the sampler is a core-cutting duralumin tube. The cutting end is fitted with a 1.485-inch-inside-diameter case-hardened steel cutter. Water equivalent of the snow sample is determined by weighing with a spring scale with a large circular dial. The diameter of the snow core is such that its weight in ounces is equivalent to inches of water. To prevent snow cores sticking in the sampler, and snow freezing to the outside of the tube, all surfaces are kept polished by frequent applications of a high carnauba content paste automobile finish wax, in accordance with

Figure 125. Weighing a snow tube and core of snow.

recent practices developed by snow surveyors. Figure 125 shows a pair of snow surveyors weighing the tube and core of snow.

F. Streamflow measurements

1. *St. Louis Creek Gaging Station.* The St. Louis Creek Gaging Station is shown in figure 2 and is described in Water Supply Paper No. 1343 [94], "St. Louis Creek near Fraser, Colorado, *Location*—lat. 39°54′30″, long. 105°52′45″, in sec. 34, T. 1S., R. 76 W., on left bank 300 feet downstream from West St. Louis Creek and 4 miles southwest of Fraser. *Drainage area*—32.8 square miles. *Water stage recorder*—datum of gage is 8,980.17 feet above mean sea level, unadjusted."

Records are available beginning with October 1933. Extremes, including water year 1954, are: maximum 470 c. f. s., June 15, 1952; minimum 4.5 c. f. s., February 23, 1935. The Geological Survey evaluates the records as "good" except for periods of ice effects which are "fair." There has been no regulation or diversion above the St. Louis Creek Gaging Station during the period covered by analyses described in this report.

A view of the St. Louis Creek Gaging Station is shown in figure 126. Stream gage heights are recorded by a Stevens Model A-35 recorder. Data are obtained in the winter during the months of October-April, inclusive, with the aid of a 15-inch depth of oil in a 14-inch-diameter cylinder within the gage house well.

2. *Fool Creek Gaging Station.* The Fool Creek Gaging Station is designed to handle year-round streamflow in a region where winter tem-

Figure 126. Looking upstream toward St. Louis Creek gaging station. April 1950.

peratures of −40° F are not uncommon. Included in the design of the station are the following elements: (a) rock and masonry cut-off walls; (b) broadcrested weirs; (c) San Dimas flume; (d) stillwell; and (e) built-in ground-water well. The station has a range in measuring capacity of from 0.08 to 60.0 c. f. s. from a drainage area of 1.11 square miles. Spring and summer flows are measured through flume and weirs, while winter flows have been measured by means of a special orifice plate inserted as a bulkhead in the downstream section of the flume. A ground-water well, constructed as an integral unit of the station, furnishes information on ground-water fluctuations in the valley-fill material adjacent to the weir section. Details of the gaging station are shown in figures 127 and 128.

Functions of the essential elements in the gaging station are as follows:

(a) The masonry wall across the valley bottom prevents the stream from meandering away from the gaging section, insures the diversion of all surface flow through the section, and reduces subsurface flow to a practical minimum.

(b) The pair of 9-inch wing walls that flank the gaging section serve the dual purpose of anchoring the gaging section and of forcing subsurface flow to the surface where it can be measured by flume and weirs.

(c) The 4- and 6-foot broad-crested weir sections measure maximum spring flows.

(d) The 1-foot-wide San Dimas flume measures normal summer flows.

(e) The orifice plate measures minimum winter flows.

(f) The stillwell measures the depth of water in the flume and weirs.

(g) The ground-water well measures fluctuations of ground water in the valley-fill material adjacent to the gaging section.

When excavating for the footings and walls of the gaging station, it was found that the valley fill was very gravelly and porous.

Figure 127. Looking upstream at Fool Creek gaging station, June 1949.

The design for the station as constructed provides for continuous, year-long measurement of flow rates. For measurement of the normal range in flow, a 1-foot San Dimas flume is set in the stream channel. This flume is 3 feet deep and 6 feet long below the end of the cylindrical entrance transition. Pressures are measured at the longitudinal midpoint of the flume. At the left side and 2½ feet above the floor of the flume was constructed a broadcrested weir 4 feet wide, with a top slope of 1 percent downstream. In combination with the flume, this weir is expected to handle all flows but the possible maximum flood. To provide for streamflow of extreme magnitude, a second broad-crested weir is included above the first; this one is 6 feet wide. Just above the downstream end of the 1-foot flume, slots are built into the structure to accommodate an orifice plate for measurement of low autumn and winter flow. This plate contains three bell-mouth orifices, each 2 inches in throat diameter, and is shown in figure 129. In late summer, when water depths in the flume drop to about 0.12–0.15 foot and no large flow peaks from rain may be expected, the orifice plate is installed in the flume.

A recorder installed in the recorder house measures pressure head transmitted from the 1-foot flume and broad-crested weirs to the stilling well. Charts are changed once a week. During the winter of 1940–41, a continuous record of winter flow was kept by using the orifice plate. A gasoline lantern was kept burning in the stilling well to prevent freezing and consequent errors in measurement of water stage. Winter flow through Fool Creek Gaging Station averaged 0.160 c. f. s. This winter record demonstrated that flow during this season was constant base flow and subsequent winter records were considered unnecessary. It has been observed that the flow is very uniform during the winter season. Flow does not appear to fluctuate perceptibly from year to year.

Before the first snow in the autumn, the piezometer slots are sealed watertight, the stilling well drained, and the recorder and float removed for the winter period. The appearance of the gage

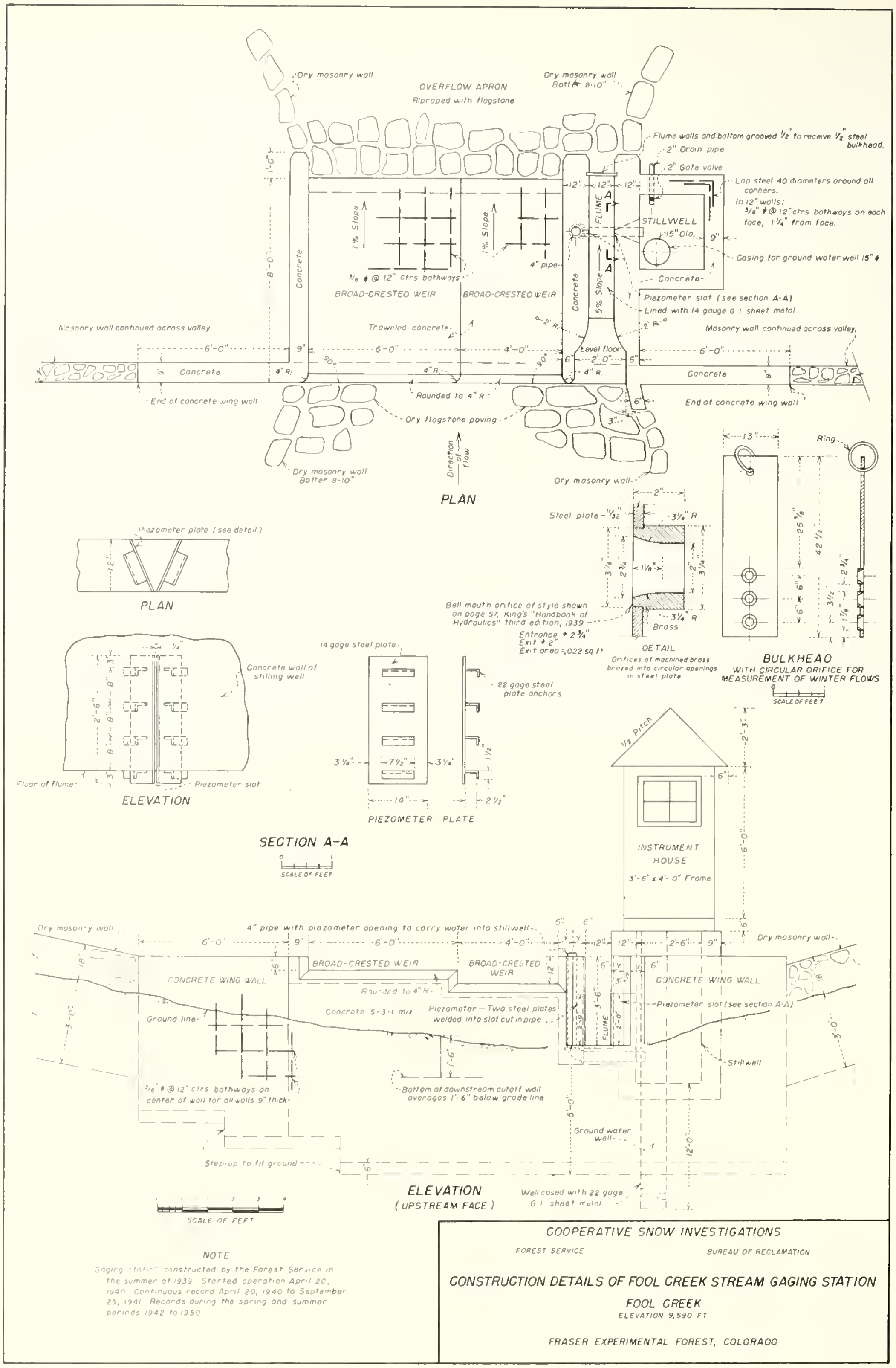

Figure 128. Construction details of Fool Creek gaging station.

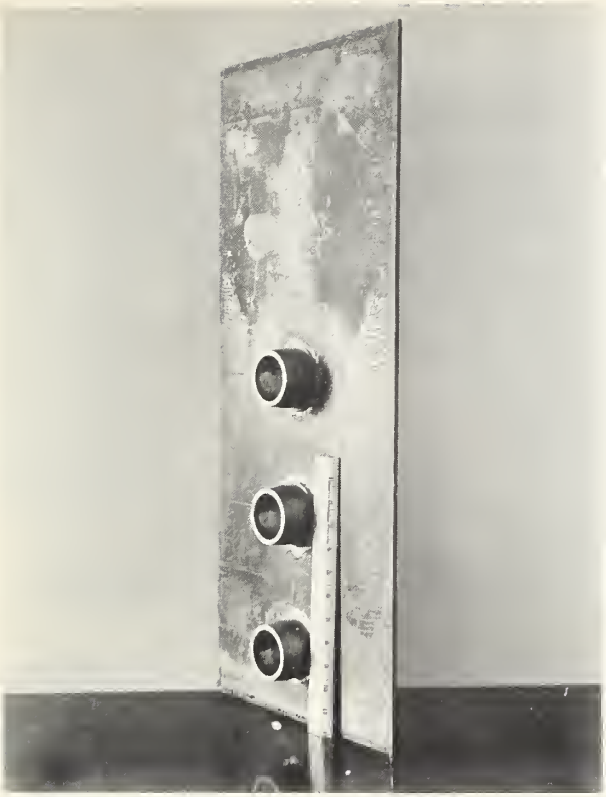

Figure 129. Orifice plate with three 2-inch bell-mouthed orifices.

the next spring just before clearing away the snow is shown in figure 130.

Flume ratings have been made under actual field operating conditions. Rating data are taken whenever possible for both the flume and broad-crested weirs. This is done by means of a velocity-head rod [99] and [100] with depths and velocities measured at four points across the flume, and at eight points across the lower broad-crested weir. Since flow over the broad-crested weir is relatively rare, special care is taken to include any exceptional summer storm or other period of unusually high flow. Stilling-well depths are recorded to correspond to all velocity-head data for both flume and weir.

3. *Ground-water wells.* The three ground-water wells in the Fool Creek Basin are located at regular intervals across the valley bottom about six feet upstream from the masonry cut-off wall. Each well has been boarded over and provision made to measure height of water level. One well on the west side of the stream has been equipped with a Friez Type FW–1 recorder for continuous measurement of ground-water fluctuations. Water level readings are made weekly from the time the wells thaw out in spring to late autumn.

4. *East St. Louis Creek Stream Gage.* The stream gaging station on East St. Louis Creek is at an elevation of about 10,000 feet. Subsurface flow is held to a minimum by locating the station in a narrow portion of the valley. The control is a trapezoidal broad-crested weir with a rectangular flume notched into the center. The station is operated from the beginning of spring melt until late in the fall when only base flow remains. No attempt has been made to measure winter flow or subsurface flow. A Friez Type FW–1 recorder is used to measure the pressure head transmitted from the weir to the stilling well.

G. Oversnow transportation

A surplus U. S. Army M–7 snow tractor transferred from the Corps of Engineers-Weather Bureau cooperative snow investigations furnished transportation over deep snow. The tractor was a 2-passenger vehicle with rear tracks and front skis. On the advice of Mr. Forest Rhodes, then Program Director of the Corps of Engineers-Weather Bureau cooperative snow investigations, several modifications were made to the tractor.

Figure 130. Fool Creek gaging station in spring before removing winter's accumulation of snow.

APPENDIX B—BASIC DATA

This section presents examples of the tabulations of basic data and derived data that have been collected in the Fraser Experimental Forest snow investigations. Except as noted below, the original recorder charts, instrument readings, and tabulations are on file with the Forest Service's Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

A. Streamflow measurements

1. *St. Louis Creek.* The original stage-height recorder charts and rating curves are on file with the Geological Survey, Water Resources Division, District Engineer, Denver Federal Center, Denver, Colo. Mean daily flows for the years 1948 to 1953, inclusive, have been published in Water Supply Papers No. 1119, 1149, 1179, 1213, 1243, and 1283. However, the cooperative snow investigations analyses were made before these water supply papers were available, and the streamflow discharges used were computed as a part of these investigations. The hourly discharges for St. Louis Creek are tabulated on tables 49, 50, 51, 52, 53, and 54.

2. *Fool Creek.* The stage-height charts and tabulations of discharges for Fool Creek are in the Forest Service files. Discharges are tabulated on tables 55, 56, and 57.

B. Air temperatures

Hourly values of air temperatures were tabulated from the thermograph trace of the hygrothermograph in the form illustrated by figure 131.

Table 49—Hourly values of streamflow during the period May 12 to June 6, 1948, St. Louis Creek near Fraser, Colo. Area: 32.8 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND*]

Date 1948	1	2	3	4	5	6	7	8	9	10	11	Noon	1	2	3	4	5	6	7	8	9	10	11	Mid't
May 12																								22
13	21	18	15	16	17	20	22	24	30	25	24	24	24	23	24	26	27	29	30	31	31	31	31	30
14	30	29	28	28	27	27	27	26	25	25	26	27	30	33	38	42	46	51	52	52	52	51	51	48
15	47	46	45	44	42	41	39	38	37	36	36	37	39	42	46	51	56	62	65	66	66	65	62	61
16	59	58	55	54	49	48	48	52	48	46	46	46	49	52	59	65	72	77	79	80	80	79	77	74
17	74	72	70	66	65	64	59	59	58	58	58	62	65	72	80	87	98	104	105	104	102	100	98	94
18	91	89	87	84	82	80	77	76	74	74	72	72	74	77	80	86	91	98	100	102	100	100	100	98
19	96	94	92	91	89	89	86	86	86	86	86	89	91	98	104	107	117	122	126	126	124	124	120	120
20	117	111	109	107	104	100	100	100	98	98	96	98	100	107	117	131	142	155	152	152	148	142	140	135
21	131	128	126	124	122	120	120	117	115	113	113	113	117	120	131	150	155	162	165	165	165	162	160	155
22	152	148	142	140	135	131	131	128	126	124	124	124	126	131	142	160	170	180	180	178	175	170	168	168
23	165	160	155	148	142	140	135	131	131	128	128	128	131	135	142	152	158	162	165	168	165	162	160	155
24	152	150	148	142	140	135	135	131	131	131	131	128	131	133	135	138	140	142	142	142	142	142	140	135
25	133	131	131	131	128	128	128	126	126	126	126	126	126	128	135	148	160	165	168	165	162	158	155	152
26	150	145	142	140	135	131	131	131	128	128	128	128	128	128	128	128	128	128	128	128	128	128	128	128
27	126	124	124	124	124	124	120	120	117	117	117	117	117	120	124	128	138	148	152	155	152	150	145	142
28	142	140	140	138	135	133	131	131	131	131	128	128	131	133	142	155	165	165	165	165	162	158	155	152
29	148	142	142	140	138	135	131	131	131	131	131	131	128	128	131	131	133	140	140	140	140	140	138	138
30	135	135	133	133	131	131	128	128	128	128	128	128	128	131	138	152	165	168	170	172	172	172	172	172
31	168	165	162	160	155	155	152	148	142	142	140	140	150	160	168	175	178	180	180	180	180	180	180	178
June 1	175	172	170	170	168	165	162	158	152	150	148	150	155	165	170	178	180	185	191	191	191	191	185	185
2	182	180	178	178	175	172	170	168	168	165	165	168	168	180	191	206	221	239	239	239	236	233	230	227
3	221	215	209	203	197	191	182	180	175	172	172	175	180	191	212	230	239	242	242	239	239	236	230	224
4	221	215	206	203	197	191	188	182	180	178	178	175	178	185	200	218	230	233	233	233	230	224	221	215
5	209	203	197	191	188	185	180	178	175	172	172	170	170	180	194	209	221	224	230	227	224	221	215	209
6	206	200	194	191	185	180	180	178	175	172	170	170	175											

* Derived from original recorder chart available at Denver, Colorado, District Office, Geological Survey, Department of the Interior.

Table 50—Hourly values of streamflow during the period May 10 to June 26, 1949, St. Louis Creek near Fraser, Colo. Area: 32.8 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND*]

Date 1949		1	2	3	4	5	6	7	8	9	10	11	Noon	1	2	3	4	5	6	7	8	9	10	11	Mid't
May	10														28	30	32	34	34	36	36	36	37	37	36
	11	36	36	35	34	34	33	33	33	33	32	32	32	32	32	32	33	34	36	39	41	43	44	45	46
	12	46	46	45	44	43	41	40	39	38	38	38	40	43	45	47	49	49	50	50	49	49	47	46	45
	13	44	43	43	41	41	40	39	39	39	39	39	39	39	39	39	40	41	41	41	41	41	40	39	39
	14	39	39	38	37	37	37	36	36	36	36	36	36	37	41	44	46	47	47	47	47	49	49	49	50
	15	49	49	49	47	47	46	45	45	45	45	45	46	47	51	54	56	59	60	60	60	60	60	59	60
	16	61	61	60	58	56	56	55	54	54	54	54	55	55	58	58	58	58	59	60	61	61	61	60	59
	17	58	58	56	56	55	55	54	54	52	52	52	52	51	51	51	51	51	51	51	51	51	51	50	50
	18	49	49	49	49	49	47	47	47	47	47	47	47	47	47	49	50	51	50	50	50	49	49	49	49
	19	47	47	46	46	46	46	45	45	45	45	45	45	45	46	47	49	49	50	51	51	51	51	51	51
	20	50	50	49	49	49	49	47	47	47	46	46	46	46	46	46	46	45	45	45	45	45	45	45	45
	21	44	44	43	43	43	43	43	43	43	43	43	43	43	43	44	44	45	45	45	44	44	44	43	43
	22	43	43	43	43	41	41	41	40	40	40	40	41	41	41	43	43	43	43	43	44	43	43	43	41
	23	41	41	41	41	40	40	40	40	39	39	39	39	39	39	40	41	43	44	45	45	45	45	45	45
	24	44	44	44	43	43	43	43	41	41	41	41	41	41	41	43	44	46	49	51	52	52	52	52	52
	25	52	52	51	50	49	49	49	47	47	46	46	46	46	47	49	54	59	64	67	69	70	70	69	69
	26	67	66	64	63	63	60	60	59	58	56	56	56	56	58	61	67	75	82	84	85	87	87	85	84
	27	82	80	78	77	75	75	75	74	72	70	69	69	69	69	70	74	75	78	80	82	84	84	84	84
	28	84	84	84	80	80	77	75	75	75	75	75	75	77	77	78	80	84	85	87	89	91	93	93	94
	29	94	94	93	91	89	87	85	85	84	84	84	84	84	84	84	87	91	94	98	102	102	102	100	98
	30	96	96	94	94	93	93	89	89	87	85	85	84	84	85	89	93	98	102	105	107	107	105	105	102
	31	102	102	100	98	98	98	94	94	93	93	89	89	87	87	87	87	87	87	87	87	87	85	85	84
June	1	84	84	82	82	82	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	78	78	77	77
	2	77	75	75	75	75	75	74	74	74	74	72	72	72	72	72	74	72	72	72	72	72	72	72	72
	3	72	72	70	70	70	70	69	69	69	69	67	67	67	67	67	69	70	72	72	74	74	74	74	75
	4	75	75	75	74	74	72	72	70	70	70	70	72	72	75	78	84	89	93	94	94	94	93	91	87
	5	85	84	80	80	78	78	78	78	77	77	77	77	77	80	85	93	100	107	111	113	113	111	109	109
	6	107	102	102	100	98	98	98	96	94	93	93	93	93	93	94	98	102	105	107	109	105	105	102	100
	7	98	98	96	94	94	94	94	93	93	93	93	93	93	93	93	94	98	102	102	102	102	100	100	98
	8	98	94	94	93	93	93	91	91	91	91	91	93	91	91	93	94	96	98	102	107	111	116	118	118
	9	118	116	116	116	116	116	116	113	111	109	111	111	113	116	120	125	128	132	135	138	138	135	135	132
	10	132	130	128	128	125	125	125	125	116	116	116	113	113	116	118	125	130	135	138	138	140	140	138	138
	11	135	135	135	132	132	130	128	125	125	120	120	120	120	125	132	140	154	166	175	181	184	184	181	181
	12	175	172	166	163	157	154	151	148	145	145	142	151	166	172	178	190	196	205	214	217	220	223	220	217
	13	211	202	196	196	190	187	184	181	178	175	172	172	172	178	187	196	202	211	211	214	214	214	214	214
	14	211	211	205	199	196	190	187	184	181	175	175	172	175	178	187	196	205	214	214	214	211	211	205	202
	15	199	193	190	187	184	181	181	178	175	172	166	166	166	175	184	199	211	220	226	226	226	226	220	214
	16	211	208	202	199	196	193	190	187	181	181	181	184	196	211	241	259	262	265	265	265	265	265	259	259
	17	253	250	247	241	238	229	226	220	214	211	211	211	226	241	250	253	253	256	259	265	259	262	262	262
	18	259	256	256	253	250	241	238	232	223	217	217	217	220	226	229	232	235	241	244	244	244	241	241	238
	19	232	229	223	220	214	211	205	202	199	199	193	193	202	217	235	253	256	256	256	256	256	250	247	250
	20	247	241	232	226	220	214	211	208	205	199	199	202	205	220	238	247	250	253	253	253	253	253	250	244
	21	241	235	229	226	217	214	208	202	199	199	196	196	202	214	238	250	253	262	259	259	259	259	253	250
	22	244	241	238	229	223	214	211	208	205	202	199	199	202	217	232	244	250	250	250	250	247	247	244	241
	23	238	232	226	220	214	211	208	208	205	205	199	199	205	217	235	241	241	244	247	250	250	244	238	232
	24	223	214	211	205	202	199	193	190	184	187	184	184	184	187	193	196	196	196	193	190	190	187	187	184
	25	184	184	181	181	181	178	175	175	175	175	175	175	175	178	184	193	202	208	208	208	199	196	193	190
	26	187	184	184	184	184	181	181	178	175	175	175	175	175	175	178	184	187	187	187	187	190	187	187	187

* Derived from original recorder chart available at Denver, Colorado, District Office, Geological Survey, Department of the Interior.

Table 51—Hourly values of streamflow during the period May 11 to June 29, 1950, St. Louis Creek near Fraser, Colo. Area: 32.8 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND*]

Date 1950	1	2	3	4	5	6	7	8	9	10	11	Noon	1	2	3	4	5	6	7	8	9	10	11	Mid't
May 11	20	19	18	16	15	15	16	18	21	20	21	21	21	21	22	24	26	27	28	28	28	27	27	25
12	25	24	23	22	20	19	20	22	24	23	22	22	23	24	24	25	26	27	27	27	26	26	25	25
13	24	24	24	24	23	22	22	22	22	22	22	23	25	27	28	29	30	30	30	30	29	28	28	27
14	27	27	26	26	24	23	26	24	24	24	24	24	25	27	28	31	32	34	34	35	34	34	33	32
15	32	32	32	31	29	29	28	28	28	28	28	28	29	30	30	31	32	34	34	35	34	34	33	33
16	32	32	32	31	30	30	29	28	28	28	28	29	30	32	33	35	37	39	40	42	42	42	41	40
17	40	39	38	37	37	35	35	35	34	34	34	36	39	42	46	51	56	58	59	59	58	56	56	55
18	55	52	52	49	48	47	46	45	44	42	42	42	42	42	42	42	42	44	44	42	42	42	42	41
19	40	39	39	38	35	32	34	40	40	39	37	37	39	40	42	45	47	49	51	51	49	48	46	46
20	45	44	42	42	41	40	39	39	39	39	38	38	39	41	44	48	52	55	58	58	56	56	55	54
21	52	51	48	48	45	42	45	49	44	42	42	44	45	47	52	59	66	72	74	74	74	72	72	71
22	68	66	65	62	59	59	58	56	55	55	54	54	55	58	64	72	80	84	87	87	87	86	86	82
23	80	76	74	72	71	70	68	66	65	62	62	62	62	65	72	77	82	87	91	92	91	91	89	87
24	86	84	80	77	76	74	72	72	71	70	70	70	71	72	74	76	79	80	82	84	86	84	82	80
25	79	77	77	76	74	72	72	72	71	71	70	65	66	66	66	66	66	66	68	68	66	65	62	62
26	62	62	62	62	61	59	59	59	61	62	62	59	58	56	56	56	56	55	55	55	55	54	54	52
27	52	51	51	51	51	51	51	51	49	49	49	49	51	51	52	54	55	55	55	54	52	52	52	51
28	49	49	48	48	48	48	47	47	47	47	48	49	51	54	58	59	61	61	59	58	58	56	55	54
29	52	52	52	51	49	48	48	48	48	48	47	48	48	48	48	49	51	52	54	54	54	54	54	52
30	52	51	51	49	48	48	48	48	47	47	47	47	47	49	52	59	66	72	76	77	79	77	77	77
31	76	74	72	71	70	68	66	66	65	65	64	62	64	66	74	82	91	96	100	102	100	98	96	94
June 1	94	92	89	86	84	82	80	79	77	77	77	77	77	80	89	102	113	122	126	126	126	124	122	117
2	115	113	109	105	102	100	98	98	98	96	94	94	94	98	107	114	126	128	131	133	135	135	135	133
3	131	128	124	122	120	115	113	109	107	107	105	105	105	104	104	104	102	100	98	96	94	94	94	92
4	91	91	89	89	87	86	86	86	86	86	87	89	91	94	96	96	96	96	96	96	94	94	92	91
5	89	87	86	86	86	86	86	86	86	86	86	86	86	87	92	100	107	115	122	124	126	124	124	122
6	120	117	115	113	111	109	107	107	105	104	102	100	104	109	120	135	155	165	170	172	172	170	168	165
7	160	155	148	142	140	135	133	131	128	126	126	126	126	131	142	165	180	188	191	191	185	180	172	168
8	165	160	158	152	145	140	135	135	133	131	131	131	131	131	131	133	135	138	138	138	135	133	131	131
9	128	128	126	124	124	124	124	122	122	122	120	117	120	122	126	131	142	155	160	162	160	158	152	145
10	142	138	133	131	128	128	128	128	128	131	131	131	133	135	142	168	182	197	206	215	218	215	215	206
11	200	194	185	180	178	175	172	165	160	155	152	152	158	170	182	212	230	236	239	239	236	236	230	233
12	227	221	212	206	197	194	188	182	180	175	172	170	175	180	200	221	239	245	248	251	251	251	245	242
13	236	224	218	206	200	191	188	182	180	178	178	175	178	182	203	224	242	245	248	251	260	260	254	251
14	248	242	236	227	221	209	203	197	194	191	188	185	188	197	224	245	254	260	263	266	260	263	260	260
15	257	254	245	236	227	218	209	206	200	197	194	191	194	206	236	251	263	260	254	257	260	260	260	263
16	263	260	254	251	248	245	239	236	227	224	221	227	242	257	266	266	269	275	284	284	281	278	278	275
17	269	266	260	263	266	260	257	251	248	245	242	245	251	266	266	272	278	281	284	287	296	290	281	275
18	266	266	269	260	260	257	251	248	242	239	236	233	230	233	245	257	260	266	269	266	260	257	254	254
19	245	239	239	233	224	215	209	206	200	203	200	200	200	206	209	224	236	239	239	236	230	224	221	218
20	215	209	203	197	197	197	194	191	191	191	191	191	191	191	194	200	209	215	215	215	212	203	197	194
21	194	191	191	191	188	185	188	188	185	185	185	185	191	194	197	200	203	206	206	206	209	203	197	197
22	197	197	194	191	191	188	185	185	182	180	178	178	178	178	180	182	185	188	191	191	188	188	188	185
23	185	182	180	178	175	172	172	170	168	168	168	168	168	172	180	182	185	188	188	188	188	191	188	188
24	185	185	182	180	180	178	175	170	168	165	162	162	165	170	178	182	188	191	191	188	188	188	185	185
25	185	182	180	178	178	175	172	170	168	162	158	155	158	160	165	170	178	180	182	182	180	178	172	170
26	168	162	160	158	155	152	150	148	148	145	142	142	142	142	145	152	158	162	165	168	165	165	162	160
27	158	155	152	150	148	142	142	140	140	138	138	135	135	135	140	142	145	148	150	150	150	148	148	145
28	142	142	140	140	138	135	135	135	133	133	133	131	131	133	133	135	135	138	140	140	142	142	142	140
29	138	135	135	135	135	133	133	131	131	131	131	131	131	131	133	135	135	135	135	135	135	135	135	133

*Derived from original recorder chart available at Denver, Colorado, District Office, Geological Survey, Department of the Interior.

Table 52—Hourly values of streamflow during the period May 15 to June 30, 1951, St. Louis Creek near Fraser, Colo. Area: 32.8 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND*]

Date 1951	1	2	3	4	5	6	7	8	9	10	11	Noon	1	2	3	4	5	6	7	8	9	10	11	Mid't
May 15	27	27	27	27	27	26	26	25	25	25	25	26	27	28	31	35	37	37	38	39	40	39	39	39
16	39	38	37	37	36	36	35	34	34	34	34	34	36	38	41	44	47	49	50	51	51	51	51	51
17	49	47	47	45	45	45	43	43	43	43	43	43	43	43	44	46	47	47	50	51	54	52	52	52
18	51	50	50	49	47	47	46	45	45	45	45	45	45	47	49	51	52	54	54	54	54	52	51	51
19	51	51	50	49	49	47	47	46	45	46	46	45	46	47	50	52	56	58	60	62	63	63	63	63
20	63	62	60	60	58	56	56	54	54	54	52	52	56	57	58	62	63	66	68	70	70	70	70	68
21	66	66	64	63	63	62	62	60	58	57	56	56	56	56	58	60	63	70	75	77	77	75	73	71
22	71	70	66	66	64	63	63	62	62	60	60	62	62	64	68	73	75	77	79	79	79	80	80	80
23	79	79	77	75	75	73	71	71	70	70	68	68	70	71	79	80	82	86	88	88	88	88	86	84
24	80	80	80	80	79	79	79	79	79	77	79	77	79	80	84	86	88	90	88	86	84	84	80	80
25	80	80	80	79	79	79	77	75	75	73	73	75	79	79	80	80	82	84	86	88	88	88	88	86
26	86	84	82	82	80	80	80	79	79	79	79	80	80	80	84	88	88	90	94	94	96	96	96	96
27	96	94	92	90	90	88	88	86	84	84	84	88	94	100	107	112	120	125	130	133	133	130	130	130
28	127	127	125	122	122	120	117	114	112	112	112	112	120	127	142	151	160	175	175	175	178	172	166	163
29	160	157	154	151	151	145	148	148	145	145	139	139	142	145	145	148	151	151	151	151	154	151	151	151
30	151	151	151	151	151	148	145	145	142	142	142	145	148	151	166	187	199	211	211	214	211	202	199	196
31	193	184	184	181	175	169	166	163	163	160	160	160	163	175	193	211	217	217	220	214	214	214	211	205
June 1	202	199	193	190	190	184	175	172	169	166	166	169	166	163	160	154	154	154	154	151	148	148	145	145
2	142	139	139	142	142	139	139	139	139	136	136	136	136	136	136	136	136	136	136	139	136	133	130	130
3	130	127	125	125	125	125	122	122	122	120	122	122	122	122	122	122	122	120	117	114	112	112	112	109
4	109	107	107	107	104	104	104	104	104	104	107	109	112	114	117	114	114	112	112	109	107	107	107	104
5	104	104	104	104	104	102	102	100	100	100	100	98	100	100	100	100	102	104	104	104	104	104	104	104
6	102	102	100	100	100	98	98	98	98	98	98	96	96	96	98	100	100	102	104	104	104	104	104	104
7	104	104	102	102	102	100	100	98	98	98	98	96	96	98	98	100	104	104	104	104	107	107	107	104
8	104	104	104	104	104	104	104	104	102	100	100	100	100	102	104	104	107	109	109	109	112	109	109	109
9	109	107	107	104	107	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	107	107	109	109
10	109	107	107	104	104	104	107	104	104	104	104	104	104	104	104	107	112	117	120	117	114	109	109	109
11	107	107	104	107	104	104	104	104	104	104	104	104	107	107	107	104	107	104	104	104	104	104	104	104
12	102	102	102	102	102	100	100	100	98	98	98	98	98	100	100	102	104	104	104	104	104	104	104	104
13	104	104	104	104	104	102	102	102	100	100	100	100	100	100	102	107	109	112	120	122	122	125	125	122
14	122	122	122	120	120	117	114	114	112	112	112	112	112	114	120	125	127	130	130	133	136	133	133	133
15	133	133	130	130	127	125	127	125	125	122	122	120	122	125	130	136	142	151	157	163	166	166	160	160
16	160	154	154	154	154	154	151	151	151	148	148	148	151	154	157	172	187	196	202	205	205	199	202	202
17	204	199	199	196	196	190	184	181	181	175	175	175	178	187	208	214	226	241	259	265	274	289	301	304
18	301	307	310	304	301	295	289	289	289	286	283	286	289	289	289	295	298	295	295	301	295	295	295	292
19	289	286	289	286	289	289	289	289	286	286	283	286	286	286	289	286	289	292	295	295	295	295	295	292
20	295	295	295	295	292	292	292	292	289	289	289	289	289	292	295	301	301	304	307	313	316	320	326	342
21	345	352	361	368	374	368	364	364	358	352	348	342	339	339	345	352	355	361	364	361	361	361	355	352
22	345	339	336	332	329	326	320	316	316	310	310	304	304	307	307	304	304	304	304	304	304	301	301	301
23	301	298	295	295	295	295	292	289	289	289	286	286	286	286	286	289	289	295	295	295	295	295	289	289
24	286	286	280	280	277	274	271	265	265	259	256	256	256	262	271	283	289	295	295	295	295	295	295	292
25	289	289	286	283	280	277	274	271	268	262	259	259	265	277	289	298	304	310	316	316	316	310	304	304
26	304	301	301	298	295	295	295	289	286	286	283	280	283	289	301	304	307	310	307	307	307	304	304	304
27	301	301	295	295	295	292	292	289	286	286	286	283	286	292	301	304	310	316	320	316	316	310	310	304
28	301	295	295	292	292	289	286	286	286	289	286	286	289	289	292	295	298	295	298	295	295	295	295	295
29	295	292	289	289	289	286	286	283	280	277	274	274	274	283	289	292	289	289	289	289	289	286	286	283
30	280	280	277	274	274	268	265	259	259	259	259	253	256	268	280	286	289	295	295	295	295	292	292	286

Derived from original recorder chart available at Denver, Colorado, District Office, Geological Survey, Department of the Interior

Table 53—Hourly values of streamflow during the period May 25 to June 25, 1952, St. Louis Creek near Fraser, Colo. **Area: 32.8 square miles**

[RATE OF RUNOFF—CUBIC FEET PER SECOND*]

Date 1952	1	2	3	4	5	6	7	8	9	10	11	Noon	1	2	3	4	5	6	7	8	9	10	11	Mid't
May 25	51	51	50	50	50	50	50	50	49	50	50	50	50	51	52	54	57	58	60	60	60	60	60	60
26	60	60	58	58	57	57	57	57	56	56	56	56	56	57	.60	62	66	68	69	68	68	66	66	64
27	64	64	63	63	62	60	60	60	58	58	58	58	60	63	64	66	68	68	68	68	68	68	68	68
28	68	68	66	66	66	66	64	64	64	64	64	64	66	68	68	69	71	73	74	76	78	78	78	78
29	74	74	73	73	71	71	71	71	71	69	69	71	73	76	80	81	85	87	91	92	94	96	96	96
30	94	94	92	92	91	91	89	89	89	87	89	89	89	91	92	94	96	98	100	100	102	102	104	102
31	102	102	100	100	98	98	98	96	96	94	94	94	94	98	100	102	104	108	110	112	115	115	117	117
June 1	115	115	112	110	108	108	108	106	106	106	104	104	106	108	112	117	123	125	127	127	127	127	127	125
2	125	125	123	123	121	121	119	119	117	117	115	115	115	117	121	125	127	130	132	134	136	136	136	136
3	136	136	134	134	134	132	132	132	130	130	130	130	130	132	138	150	168	191	228	246	249	246	242	235
4	228	224	221	218	210	210	218	224	228	224	221	221	218	221	228	235	242	246	249	249	249	249	246	242
5	242	238	232	224	221	210	207	200	194	188	188	188	194	207	228	246	263	278	278	278	282	282	282	286
6	282	278	274	274	266	263	260	256	252	246	242	246	260	270	274	274	282	294	294	302	314	314	306	306
7	302	298	290	290	286	282	278	274	270	270	270	266	270	274	286	298	322	330	330	334	346	338	342	350
8	346	342	330	326	318	310	306	302	294	290	282	286	290	294	302	322	334	350	354	359	354	354	359	354
9	359	359	350	346	342	330	322	314	310	306	302	298	302	314	334	354	372	382	386	390	390	405	405	400
10	364	359	350	338	334	326	326	318	306	310	310	306	322	330	354	354	377	405	425	450	440	465	450	425
11	386	390	377	368	372	364	350	346	338	334	346	342	346	364	368	368	372	364	368	368	372	372	368	368
12	364	359	354	359	346	342	338	334	330	326	322	314	318	326	346	372	382	395	405	415	410	420	410	405
13	400	395	390	382	368	354	346	342	334	326	326	326	326	330	346	359	368	382	395	410	415	410	390	382
14	372	364	354	346	342	334	330	322	318	314	310	306	314	322	338	354	372	390	415	410	410	390	382	377
15	377	372	359	354	354	346	342	334	330	326	326	322	330	346	368	405	420	430	440	465	450	440	460	435
16	410	395	386	382	372	364	346	346	342	342	338	330	326	322	326	330	334	342	342	338	334	326	322	318
17	306	306	302	298	298	290	286	278	274	270	266	263	260	263	270	282	290	302	302	302	298	294	290	286
18	282	274	266	263	260	256	252	249	246	246	242	242	238	242	246	252	256	256	260	260	263	260	256	256
19	252	249	249	246	246	246	238	235	232	232	228	228	232	246	263	282	294	306	310	310	306	302	298	286
20	278	266	263	260	256	252	249	242	238	235	235	235	235	246	263	286	306	318	314	314	302	298	290	282
21	274	266	263	256	249	246	242	238	232	232	232	228	228	232	235	246	256	266	266	266	256	252	249	242
22	238	232	232	228	228	224	221	221	221	218	218	214	214	214	218	218	224	232	232	232	232	228	221	218
23	214	214	210	210	210	210	207	207	207	207	204	204	204	204	207	210	210	210	210	214	214	210	210	207
24	204	204	204	200	197	197	197	197	197	197	194	194	194	194	197	200	200	204	207	207	207	207	207	207
25	207	204	204	204	200	200	197	197	194	191	191	191	191	194	197	200	204	207	207	207	207	207	204	204

* Derived from original recorder chart available at Denver, Colorado, District Office, Geological Survey, Department of the Interior.

Table 54—Hourly values of streamflow during the period May 21 to June 27, 1953, St. Louis Creek near Fraser, Colo. Area: 32.8 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND*]

Date 1953	1	2	3	4	5	6	7	8	9	10	11	Noon	1	2	3	4	5	6	7	8	9	10	11	Mid't
May 21	14	14	14	14	14	14	14	14	14	14	14	16	18	20	23	26	27	27	29	30	31	31	31	30
22	29	28	27	27	27	27	25	25	25	25	25	25	27	30	34	38	41	44	45	46	46	45	44	43
23	41	40	39	37	37	36	35	34	34	33	32	33	35	38	41	45	49	50	52	52	52	52	51	49
24	47	47	46	45	44	43	41	40	39	38	39	41	45	51	62	68	74	81	83	80	74	73	71	69
25	68	66	62	58	52	51	54	50	49	47	47	47	51	57	66	73	80	81	81	81	80	80	83	78
26	73	69	68	66	63	62	60	57	56	56	56	56	57	62	68	73	83	81	83	83	85	85	83	81
27	81	81	80	80	76	80	78	76	73	73	74	78	83	81	87	91	98	110	119	119	125	127	130	127
28	130	130	127	121	119	115	108	104	98	96	96	98	108	119	136	143	148	155	165	160	152	150	145	141
29	138	134	132	130	130	125	123	121	117	112	108	108	106	108	110	110	110	108	104	100	98	98	94	92
30	91	91	91	89	89	89	89	87	87	85	85	85	85	89	91	98	112	119	119	117	115	110	106	100
31	98	94	92	91	91	91	89	89	89	89	89	89	89	91	110	127	132	132	132	132	132	132	130	130
June 1	127	123	121	117	112	110	108	106	102	100	98	98	100	104	108	117	123	130	132	132	134	132	132	132
2	130	130	130	127	127	125	123	121	121	119	117	117	119	130	132	145	158	162	162	162	160	152	148	143
3	138	136	136	136	134	132	132	130	127	125	123	123	125	132	136	141	148	152	150	148	143	141	138	136
4	136	136	136	132	132	130	130	127	125	123	121	121	125	130	132	132	132	132	132	132	132	132	132	130
5	130	127	125	123	121	119	117	115	115	112	110	110	110	112	108	112	117	119	123	125	123	123	123	121
6	119	117	115	115	112	110	108	108	106	106	104	102	102	102	104	106	112	117	121	123	125	123	125	121
7	121	119	117	117	115	110	108	108	108	106	106	104	102	102	104	104	106	108	106	106	104	102	98	98
8	96	96	96	94	94	92	92	92	91	91	91	89	91	92	106	125	130	138	143	145	143	138	138	134
9	134	132	130	130	127	127	125	123	119	117	117	115	117	125	130	150	179	194	200	204	207	207	207	197
10	191	185	176	165	158	152	148	141	138	136	134	134	138	152	185	207	218	238	242	242	238	224	218	214
11	207	200	204	197	194	188	179	176	168	162	162	162	176	185	200	210	228	242	246	228	238	235	238	228
12	228	224	221	218	214	210	210	207	204	204	204	207	214	235	260	263	274	294	290	282	286	282	290	282
13	278	274	266	256	249	246	242	232	224	224	224	228	246	266	290	314	322	338	359	354	350	326	318	318
14	302	306	294	286	278	270	263	260	252	246	246	249	252	263	278	282	282	282	286	294	294	282	278	274
15	270	263	256	249	242	235	228	224	221	218	218	218	221	224	242	260	270	274	274	270	263	260	249	246
16	238	228	228	221	221	218	218	214	210	207	207	207	210	221	238	249	252	260	260	260	252	246	242	235
17	228	228	224	221	218	214	210	210	207	207	204	207	210	224	242	256	263	266	270	266	266	263	256	246
18	238	235	232	228	228	224	218	214	214	214	210	224	228	238	242	242	260	274	298	318	364	377	372	334
19	318	302	294	282	278	278	298	306	302	290	282	278	274	290	302	318	314	314	306	302	298	290	286	282
20	278	274	270	263	260	249	242	238	235	235	238	238	238	238	242	246	246	246	238	235	232	228	224	224
21	218	214	210	210	207	207	204	204	204	200	200	200	200	204	207	210	210	210	207	207	204	204	200	200
22	200	200	197	194	194	191	191	188	188	185	185	188	191	191	194	200	204	204	204	200	200	197	197	194
23	194	191	191	188	185	185	179	179	179	176	176	176	179	188	191	194	197	200	200	200	197	194	194	191
24	191	185	185	179	179	176	176	173	170	168	165	165	168	173	179	185	185	182	179	179	179	176	176	173
25	170	165	165	162	160	155	152	152	150	150	145	145	143	145	148	148	150	155	158	158	152	150	148	145
26	143	141	141	141	138	138	136	134	134	132	130	130	130	130	134	136	138	138	138	138	138	138	138	138
27	136	136	132	130	130	127	127	127	125	125	123	123	123	123	123	125	127	130	130	130	130	130	127	125

* Derived from original recorder chart available at Denver, Colorado, District Office, Geological Survey, Department of the Interior.

Table 55—Streamflow during the period May 21 to June 26, 1949, Fool Creek, Fraser Experimental Forest, Colorado

Area: 1.11 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND]

Date	Hour	C. f. s.	Date	Hour	C. f. s.	Date	Hour	C. f. s.
May 21	Midnight	1.02	May 30	400A	2.71	June 7	1100A	3.37
May 22	Noon	.98		1000A	2.54		Noon	3.41
	800P	1.01		1100A	2.54		200P	3.55
	Midnight	1.00		Noon	2.57		300P	3.65
May 23	1100A	.93		100P	2.71		400P	3.68
	Noon	.95		300P	3.07		500P	3.69
	230P	1.12		430P	3.15		600P	3.69
	400P	1.18		600P	3.18		Midnight	3.53
	630P	1.24		700P	3.17	June 8	845A	3.45
	900P	1.23		Midnight	3.00		1030A	3.52
	Midnight	1.18	May 31	600A	2.77		200P	3.75
May 24	900A	1.07		1130A	2.65		415P	4.00
	1130A	1.06		200P	2.69		445P	4.08
	1230P	1.07		600P	2.72		700P	4.17
	430P	1.38		800P	2.71		715P	4.36
	530P	1.50		Midnight	2.63		730P	4.63
	630P	1.53	June 1	1130A	2.51		815P	5.11
	800P	1.53		100P	2.51		900P	5.30
	Midnight	1.47		400P	2.54		930P	5.33
May 25	400A	1.37		500P	2.51		1100P	5.07
	800A	1.32		Midnight	2.44		Midnight	4.98
	1045A	1.30	June 2	1100A	2.34	June 9	200A	4.86
	1130A	1.31		1230P	2.41		300A	4.88
	Noon	1.35		330P	2.44		430A	5.12
	200P	1.64		Midnight	2.34		530A	5.16
	300P	1.83	June 3	1100A	2.23		830A	4.90
	430P	2.01		300P	2.44		1100A	4.86
	600P	2.04		400P	2.48		1230P	4.88
	1000P	1.86		800P	2.56		100P	5.09
	Midnight	1.79		1000P	2.56		230P	5.44
May 26	300A	1.71		Midnight	2.51		400P	5.60
	500A	1.67	June 4	600A	2.41		700P	5.37
	1000A	1.61		800A	2.43		Midnight	5.18
	1100A	1.62		1000A	2.50	June 10	300A	5.11
	Noon	1.67		1230P	2.69		830A	4.88
	130P	1.98		200P	3.00		Noon	4.98
	300P	2.41		400P	3.87		200P	5.12
	400P	2.54		445P	4.03		230P	5.27
	530P	2.59		530P	4.03		400P	5.44
	1000P	2.34		600P	3.99		700P	5.56
	Midnight	2.25		900P	3.50		1000P	5.56
May 27	400A	2.12		Midnight	3.23		1100P	5.58
	1000A	1.97	June 5	600A	2.90		Midnight	5.58
	1100A	1.97		900A	2.82	June 11	600A	5.39
	Noon	2.01		1000A	2.85		930A	5.36
	200P	2.23		1100A	2.94		1130A	5.40
	400P	2.40		Noon	3.21		230P	5.85
	600P	2.47		200P	3.83		630P	6.31
	800P	2.48		230P	3.91		800P	6.40
	1000P	2.46		300P	3.94		Midnight	6.45
	Midnight	2.40		700P	3.71	June 12	1700A	6.31
May 28	600A	2.24		900P	3.57		1000A	6.31
	1000A	2.19		Midnight	3.45		215P	6.37
	1230P	2.30	June 6	300A	3.36		600P	7.70
	400P	2.68		930A	3.25		Midnight	7.70
	730P	2.79		1030A	3.25	June 13	915A	7.70
	Midnight	2.65		100P	3.31		945A	7.66
May 29	700A	2.45		250P	3.41		1100A	7.68
	930A	2.41		300P	3.55		530P	8.55
	1100A	2.45		400P	3.69		730P	8.73
	130P	2.60		500P	3.78		1030P	8.73
	200P	2.66		630P	3.76		Midnight	8.82
	400P	3.05		Midnight	3.55	June 14	1230A	8.82
	430P	3.15	June 7	600A	3.39		100A	8.97
	600P	3.21		800A	3.36		500A	8.60
	Midnight	2.90		900A	3.36		900A	8.22

Table 55—Streamflow during the period May 21 to June 26, 1949, Fool Creek, Fraser Experimental Forest, Colorado—Continued

Area: 1.11 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND]

Date	Hour	C. f. s.	Date	Hour	C. f. s.	Date	Hour	C. f. s.
May 29	1100A	8.18	June 18	Noon	10.69	June 22	500P	9.21
	1230P	8.18		345P	10.88		700P	9.04
	430P	8.94		600P	11.21		Midnight	8.22
	630P	9.27		900P	11.17	June 23	300A	8.00
	745P	9.41		Midnight	11.80		600A	7.58
	900P	9.41	June 19	530A	9.84		845A	7.69
	Midnight	9.25		815A	9.63		Noon	7.68
June 15	400A	9.03		1100A	9.34		245P	8.85
	845A	8.22		Noon	9.47		500P	8.18
	1030A	8.09		1245P	10.29		600P	8.43
	Noon	8.27		315P	11.55		Midnight	7.67
	200P	9.18		600P	12.14	June 24	345A	7.37
	400P	9.65		845P	11.65		615A	7.21
	545P	10.46		Midnight	10.80		Noon	6.90
	730P	10.57	June 20	400A	9.81		300P	7.01
	Midnight	10.50		800A	9.09		600P	6.90
June 16	300A	10.33		1030A	8.89		Midnight	6.67
	600A	9.93		Noon	9.20	June 25	315A	6.57
	930A	9.50		1245P	9.90		600A	6.40
	1130A	9.78		245P	11.07		1130A	6.14
	115P	10.80		530P	11.69		215P	6.51
	200P	11.79		830P	11.05		500P	6.52
	230P	13.27		Midnight	9.94		900P	6.32
	245P	12.58	June 21	300A	9.22		Midnight	6.18
	445P	13.12		630A	8.73	June 26	230A	6.03
	745P	13.74		1030A	8.39		345A	6.04
	Midnight	12.97		Noon	8.66		545A	5.93
June 17	430A	11.78		215P	9.96		Noon	5.76
	1945A	10.84		530P	10.70		145P	5.87
	230P	11.92		900P	10.07		545P	5.82
	215P	13.26		Midnight	9.26		630P	6.10
	600P	14.16	June 22	230A	8.89		815P	6.14
	900P	13.88		545A	8.85		Midnight	5.90
	Midnight	12.88		1030A	7.90			
June 18	500A	11.45		Noon	8.06			
	915A	10.79		145P	8.81			

Table 56—Streamflow during the period May 29 to June 26, 1950, Fool Creek, Fraser Experimental Forest, Colorado

Area: 1.11 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND]

Date	Hour	C. f. s.	Date	Hour	C. f. s.	Date	Hour	C. f. s.
May 29	600A	1.04	June 5	830A	2.52	June 10	1100P	9.12
	1045A	.99		1100A	2.50		1130P	9.00
	Noon	1.00		Noon	2.58		Midnight	9.05
	115P	1.01		100P	2.77	June 11	1215A	9.07
	215P	1.03		400P	3.67		1245A	8.96
	600P	1.12		500P	3.78		115A	9.02
	930P	1.13		600P	3.76		315A	8.71
	1100P	1.13		1100P	3.50		1015A	7.28
	Midnight	1.12		Midnight	3.44		1245P	7.57
May 30	200A	1.10	June 6	100A	3.41		215P	8.97
	1030A	1.04		430A	3.40		630P	11.21
	Noon	1.11		930A	3.23		700P	12.71
	100P	1.26		1015A	3.21		715P	11.63
	345P	1.91		1115A	3.09		745P	11.54
	530P	2.13		430P	5.24		800P	12.06
	615P	2.12		815P	5.34		815P	11.95
	900P	1.98		1030P	5.72		830P	12.64
	Midnight	1.78		Midnight	5.16		900P	11.66
May 31	300A	1.67	June 7	1015A	4.23		Midnight	11.20
	600A	1.62		1100A	4.24	June 12	115A	10.83
	1045A	1.54		1115A	4.25		245A	10.26
	Noon	1.62		Noon	4.53		645A	9.15
	1230P	1.79		500P	6.14		945A	9.54
	200P	2.34		630P	6.28		1030A	8.24
	330P	2.66		Midnight	6.07		1115A	8.44
	445P	2.77	June 8	845A	5.85		Noon	8.78
	600P	2.71		1130A	5.80		115P	9.59
	900P	2.44		Noon	5.85		300P	10.57
	1115P	2.25		115P	6.00		315P	11.17
	Midnight	2.23		245P	6.02		330P	10.99
June 1	130A	2.20		515P	5.90		500P	11.93
	1030A	2.01		715P	5.69		745P	12.59
	1115A	2.02		1030P	5.50		800P	12.55
	Noon	2.05		Midnight	5.49		815P	13.19
	1230P	2.18	June 9	145A	5.47		830P	12.51
	115P	2.32		430A	5.41		845P	13.44
	300P	3.00		930A	5.24		915P	12.45
	445P	3.21		1045A	5.21		1100P	12.06
	545P	3.20		Noon	5.30		Midnight	11.66
	700P	3.09		100P	5.57	June 13	300A	10.57
	900P	2.92		145P	5.74		400A	10.31
	Midnight	2.71		300P	5.85		415A	10.16
June 2	545A	2.49		345P	5.86		900A	9.07
	1045A	2.43		530P	5.85		1000A	8.98
	Noon	2.49		730P	5.74		1100A	9.04
	100P	2.77		915P	5.81		Noon	9.33
	230P	3.39		Midnight	5.59		245P	11.19
	315P	3.47	June 10	130A	6.10		300P	11.43
	530P	3.52		330A	6.07		400P	12.42
	700P	3.41		345A	6.25		600P	13.33
	745P	3.54		415A	6.08		815P	14.02
	815P	3.47		800A	5.69		1100P	13.15
	900P	3.49		1000A	5.58		Midnight	12.63
	Midnight	3.31		1030A	5.62	June 14	230A	11.77
June 3	230A	3.09		1045A	6.02		415A	11.07
	345A	3.06		1100A	5.78		1030A	9.04
	500A	3.13		1130A	5.67		Noon	10.09
	Noon	2.88		Noon	5.71		300P	13.15
	600P	2.72		1230P	5.94		600P	14.32
	Midnight	2.60		245P	7.02		730P	14.63
June 4	800A	2.48		415P	7.38		830P	14.41
	1045A	2.47		545P	7.57		915P	14.08
	Noon	2.54		845P	8.68		Midnight	12.85
	200P	2.82		900P	9.34	June 15	200A	12.18
	330P	2.93		930P	8.90		445A	11.13
	530P	2.93		1000P	9.02		1000A	10.10
	Midnight	2.75		1030P	8.96		1045A	10.09

Table 56—Streamflow during the period May 29 to June 26, 1950, Fool Creek, Fraser Experimental Forest, Colorado—Continued

Area: 1.11 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND]

Date	Hour	C. f. s.	Date	Hour	C. f. s.	Date	Hour	C. f. s.
June 15	1130A	10.19	June 19	100P	9.50	June 23	1030A	6.49
	Noon	10.50		130P	9.81		Noon	6.58
	100P	11.34		230P	10.17		200P	6.95
	215P	12.55		330P	10.28		315P	7.01
	230P	12.85		430P	10.18		600P	6.90
	345P	13.52		800P	9.79		Midnight	6.54
	430P	13.57		1015P	9.45	June 24	645A	6.18
	600P	14.28		1100P	9.43		1000A	6.14
	700P	14.35		Midnight	9.28		1045A	6.03
	930P	14.04	June 20	200A	9.08		Noon	6.07
	Midnight	13.19		400A	8.89		315P	6.45
June 16	400A	12.52		1000A	8.34		400P	6.36
	930A	11.45		1130A	8.30		745P	6.28
	1030A	11.58		1145A	8.37		930P	6.16
	1115A	11.99		245P	8.80		1100P	5.94
	100P	13.52		400P	8.88		Midnight	5.91
	415P	15.98		715P	8.67	June 25	345A	5.76
	630P	17.15		1015P	8.30		1000A	5.43
	700P	16.46		Midnight	8.17		Noon	5.40
	900P	15.62	June 21	915A	7.64		1230P	5.33
	Midnight	14.34		1015A	7.69		215P	5.50
June 17	345A	12.97		1100A	7.66		330P	5.58
	645A	12.17		Noon	7.73		830P	5.37
	1000A	11.57		100P	7.95		915P	5.36
	1100A	11.56		300P	7.94		1000P	5.28
	Noon	11.84		400P	8.05		Midnight	5.20
	115P	12.63		515P	8.06	June 26	230A	5.07
	200P	13.15		600P	8.04		530A	5.03
	300P	13.50		850P	7.93		730A	4.88
	500P	14.00		Midnight	7.70		1030A	4.77
	700P	14.12	June 22	400A	7.48		1100A	4.73
	800P	13.92		815A	7.09		Noon	4.67
	Midnight	12.61		1000A	6.97		145P	4.73
June 18	600A	11.88		1100A	6.99		300P	4.77
	700A	11.06		1130A	7.20		500P	4.78
	1100A	10.64		Noon	7.11		815P	4.74
	Noon	10.30		100P	7.19		845P	4.79
	1230P	10.30		215P	7.52		900P	4.72
	245P	10.74		230P	7.32		Midnight	4.66
	400P	11.23		245P	7.48			
	800P	11.21		515P	7.40			
	Midnight	10.79		600P	7.31			
June 19	315A	10.09		Midnight	6.99			
	845A	9.45	June 23	430A	6.70			
	1100A	9.28		700A	6.59			
	Noon	9.36		730A	6.64			

Table 57—Streamflow during the period June 11 to July 1, 1951, Fool Creek, Fraser Experimental Forest, Colorado

Area: 1.11 square miles

[RATE OF RUNOFF—CUBIC FEET PER SECOND]

Date	Hour	C. f. s.	Date	Hour	C. f. s.	Date	Hour	C. f. s.
June 11	1000A	3.98	June 20	130P	13.90	June 26	715A	11.32
	445P	4.13		345P	14.72		1100A	10.97
	700P	4.16		545P	15.40		Noon	11.17
	Midnight	4.04		700P	16.28		200P	12.33
June 12	1000A	3.93		730P	16.75		330P	12.59
	Noon	3.88		800P	17.04		700P	12.51
	115P	4.14		915P	17.26		Midnight	11.71
	630P	4.46		1045P	19.92	June 27	600A	10.92
	Midnight	4.38		1130P	18.93		630A	10.96
June 13	1045A	4.16		Midnight	18.83		900A	10.43
	1230P	4.20	June 21	130A	18.92		930A	10.46
	600P	4.90		145A	18.68		1015A	10.40
	1000P	4.89		215A	19.14		1100A	10.44
	Midnight	4.88		245A	18.51		1145A	10.42
June 14	1030A	4.60		315A	19.27		Noon	10.62
	200P	4.80		415A	18.72		200P	11.49
	530P	4.90		1000A	16.08		300P	11.72
	900P	5.03		1130A	15.86		515P	11.58
	Midnight	5.03		1245P	16.89		615P	11.66
June 15	1100A	4.82		345P	18.72		Midnight	10.71
	500P	5.82		415P	19.72	June 28	1000A	9.99
	800P	5.95		515P	19.12		1245P	10.31
	Midnight	6.01		700P	19.24		300P	10.52
June 16	515A	5.82		830P	18.75		500P	10.55
	1100A	5.54		Midnight	17.32		700P	10.55
	130P	6.41	June 22	545A	15.22		Midnight	10.15
	330P	7.08		1130A	13.90	June 29	300A	10.10
	545P	7.31		100P	14.20		445A	9.90
	630P	7.32		115P	14.90		1045A	9.45
	900P	7.63		145P	14.72		1215P	9.60
	Midnight	7.57		215P	14.97		130P	9.95
June 17	1030A	7.11		300P	15.17		215P	10.00
	1215P	7.29		700P	14.72		300P	10.39
	215P	8.04		Midnight	13.88		315P	10.23
	230P	8.42	June 23	430A	13.12		345P	10.44
	430P	9.40		515A	13.22		600P	10.25
	545P	9.45		545A	13.08		825P	10.01
	930P	14.69		830A	12.89		Midnight	9.59
	1145P	13.47		1150A	12.66	June 30	430A	9.25
	Midnight	13.28		400P	13.50		715A	9.11
June 18	100A	13.11		530P	13.61		915A	8.98
	1030A	11.33		815P	13.49		1100A	8.84
	215P	12.40		Midnight	12.91		1230P	8.95
	600P	13.57	June 24	915A	11.77		1245P	8.89
	730P	13.75		1145A	11.52		315P	9.29
	Midnight	13.46		330P	12.70		800P	9.25
June 19	915A	12.17		630P	12.97		Midnight	8.99
	1130A	12.22		Midnight	12.64	July 1	400A	8.73
	145P	13.41	June 25	200A	12.39		630A	8.50
	345P	14.39		215A	12.46		700A	8.55
	815P	15.12		645A	11.77		745A	8.45
	Midnight	14.90		1030A	11.16		900A	8.47
June 20	1215A	15.17		1045A	11.34		1100A	8.23
	100A	14.72		1115A	11.32		100P	8.41
	145A	14.67		145P	12.68		400P	8.75
	500A	13.90		400P	13.19		600P	8.69
	1015A	13.06		715P	13.50		630P	8.78
	1215P	13.19		Midnight	12.63		Midnight	8.40

UNITED STATES DEPARTMENT OF INTERIOR
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DATA SHEET; HOURLY RECORDS

Station HEADQUARTERS STATION FRASER EXPERIMENTAL FOREST

Data AIR TEMPERATURE °F. FROM HYGROTHERMOGRAPH TRACE

JUNE 1950

DATE	AM 1	AM 2	AM 3	AM 4	AM 5	AM 6	AM 7	AM 8	AM 9	AM 10	AM 11	NOON	PM 1	PM 2	PM 3	PM 4	PM 5	PM 6	PM 7	PM 8	PM 9	PM 10	PM 11	Mid't	SUM	MEAN	Instantaneous °F Chart Max	Instantaneous °F Chart Min
1	23	22	22	21	26	38	49	51	55	59	63	65	67	67	68	68	66	62	54	43	35	30	28	26	1108	46.2	69	21
2	25	25	25	24	24	34	46	53	57	62	65	65	67	65	61	57	53	49	41	36	33	31	31	31	1060	44.2	69	24
3	31	30	30	30	29	31	32	35	34	34	36	34	32	35	34	34	35	35	31	30	28	27	26	25	758	31.6	36	25
4	23	22	21	20	19	26	31	32	34	36	42	44	47	51	52	55	54	52	47	38	33	30	27	27	863	36.0	56	19
5	26	26	26	25	25	28	40	48	54	57	61	63	65	66	68	70	68	63	51	41	36	33	31	29	1100	45.8	70	25
6	28	27	26	26	26	36	50	58	64	66	69	69	71	72	72	72	67	63	57	53	50	54	49	47	1272	53.0	72	26
7	45	40	35	29	29	37	50	54	61	65	68	67	67	66	63	57	52	48	42	38	35	34	32	29	1143	47.6	68	27
8	29	27	23	21	22	32	40	43	46	49	51	50	49	49	51	50	49	46	41	36	29	26	23	22	904	37.7	51	20
9	21	20	19	18	22	33	43	48	50	53	56	58	60	60	62	62	61	58	48	38	32	30	27	27	1006	41.9	63	18
10	30	29	32	28	26	37	49	56	62	66	69	71	73	75	73	70	69	67	62	53	43	38	34	31	1243	51.8	75	26
11	29	28	26	25	25	31	48	56	66	70	72	75	76	77	@79	@76	@76	@76	@68	@49	42	39	35	33	1277	53.2	79	25
12	30	29	27	26	26	31	48	58	62	66	71	70	74	76	77	77	74	69	63	53	45	39	35	33	1259	52.5	78	25
13	30	30	28	28	27	31	48	57	68	71	74	76	76	74	73	76	73	67	64	54	44	38	34	32	1273	53.0	77	27
14	30	29	27	26	30	40	56	59	64	69	73	75	76	78	78	77	73	69	60	51	42	36	34	31	1283	53.5	78	26
15	29	27	26	25	29	41	54	59	68	74	77	77	79	80	78	71	69	67	62	54	48	47	43	45	1329	55.4	80	26
16	44	42	40	37	35	49	60	68	73	74	73	70	70	73	67	65	64	63	58	53	48	43	40	41	1350	56.2	76	35
17	39	38	36	34	33	39	54	63	72	74	73	77	78	77	78	79	74	70	60	45	37	33	30	29	1322	55.1	79	33
18	27	26	25	24	23	32	48	57	61	65	67	69	70	71	72	72	70	67	60	47	42	37	34	32	1198	49.9	73	23
19	30	29	29	29	29	36	50	56	62	65	66	68	69	72	66	67	64	59	57	53	47	48	44	39	1234	51.4	72	29
20	34	32	30	29	29	31	40	50	56	60	59	64	67	66	66	66	65	62	56	47	40	37	34	32	1152	48.0	69	29
21	30	29	28	27	28	38	50	58	66	68	71	70	64	60	66	62	61	59	52	44	39	35	33	31	1169	48.7	73	27
22	30	29	27	26	28	34	51	60	61	59	61	65	65	64	66	66	62	59	53	50	45	39	35	33	1168	48.7	66	26
23	31	30	30	30	34	47	55	60	66	70	72	73	71	77	75	73	71	67	61	57	48	42	38	35	1313	54.7	77	29
24	33	32	30	30	31	44	57	62	66	71	73	76	77	75	74	74	75	70	62	51	44	40	38	36	1321	55.0	79	30
25	46	47	45	41	39	49	52	56	59	60	64	64	65	68	69	68	67	64	59	47	39	36	33	31	1268	52.8	69	31
26	29	28	26	26	26	33	50	57	65	70	72	73	75	77	77	74	70	67	62	55	48	44	41	38	1283	53.5	77	26
27	35	33	31	30	31	41	54	62	67	71	71	73	73	72	73	70	69	67	59	49	42	38	36	33	1280	53.3	74	30
28	31	30	29	28	29	39	53	61	64	68	70	73	73	72	74	71	70	69	64	55	47	43	40	38	1291	53.8	74	27
29	35	33	32	31	31	41	52	57	63	66	66	65	67	66	63	69	66	61	56	50	43	40	37	35	1225	51.0	70	30
30	33	32	31	32	31	36	50	60	66	67	71	72	75	74	77	74	71	68	60	47	42	39	37	36	1281	53.4	77	31
31																												
Sums																												
Means																												

HD-41 @Estimated CHECKED BY R.R.A. TABULATED BY F.W.Rabe DATE 2/8/51

Figure 131. Example of tabulation of hourly air temperature as read from thermograph trace.

Similar tabulations are available for the following periods:

1. *Headquarters Station.* April 4 to September 29, 1947; April 1 to July 12, 1948; March 28 to July 13, 1949; and March 24 to July 31, 1950.

2. *West St. Louis Station.* October 1 to 15, 1947; March 19 to July 18, 1948; April 8 to July 13, 1949; and March 29 to July 31, 1950.

3. *East St. Louis Station.* April 28 to July 24, 1947.

4. *Fool Creek Station.* June 9 to September 26, 1949; and April 6 to July 31, 1950.

C. Relative humidity

Hourly values of relative humidity were tabulated from the hygrograph trace of the hygrothermograph in the form illustrated by figure 132. Similar tabulations are available for the following periods:

1. *Headquarters Station.* April 4 to September 30, 1947; April 1 to July 12, 1948; March 29 to July 12, 1949; and March 23 to July 31, 1950.

2. *West St. Louis Station.* October 1 to 15, 1947; March 19 to July 19, 1948; April 9 to July 13, 1949; and March 29 to July 31, 1950.

3. *East St. Louis Station.* April 28 to July 24, 1947.

4. *Fool Creek Station.* June 9 to September 26, 1949; and April 6 to July 31, 1950.

D. Degree-days

Hourly values of degree-hours above 32° F and daily total degree-days above 32° F were computed from the thermograph record of the hygrothermograph and tabulated in the form illustrated by figure 133. Similar tabulations are available for the following periods:

1. *Headquarters Station.* April 5 to June 30, 1947; April 15 to June 30, 1948; April 1 to July 12, 1949; and May 1 to June 30, 1950.

UNITED STATES DEPARTMENT OF INTERIOR
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DATA SHEET; HOURLY RECORDS

Station HEADQUARTERS STATION FRASER EXPERIMENTAL FOREST — Data Relative Humidity % From Hygrothermograph Trace

JUNE 1950

DATE	A.M. 1	2	3	4	5	6	7	8	9	10	11	NOON	P.M. 1	2	3	4	5	6	7	8	9	10	11	Mid't	SUM	MEAN	Instantaneous °F	
1	98	97	99	99	100	72	35	32	27	23	16	15	13	12	11	11	11	14	21	50	60	80	82	90	1168	48.7		
2	96	94	95	97	93	67	37	36	26	21	20	16	16	20	28	38	45	49	93	96	98	100	100	100	1481	61.7		
3	100	100	100	100	99	99	99	92	89	90	87	87	91	83	86	87	87	89	92	97	98	98	97	96	2243	93.4		
4	95	95	95	94	94	100	92	88	85	80	72	62	49	37	26	29	33	37	45	82	90	94	98	99	1771	73.9		
5	98	99	99	99	98	98	58	47	37	35	34	32	29	26	25	22	22	29	53	76	82	90	94	98	1480	61.7		
6	98	98	98	98	98	76	40	34	15	14	13	12	12	12	11	12	13	28	37	38	41	37	46	45	1026	42.8		
7	40	49	63	86	92	58	39	32	21	20	20	20	15	15	20	23	24	22	24	26	29	33	38	48	857	35.7		
8	48	50	78	82	89	52	34	28	25	26	27	27	24	24	24	25	25	26	32	45	66	83	87	89	1116	46.5		
9	89	92	94	98	96	63	37	28	26	25	22	20	17	16	16	16	16	17	45	67	80	82	90	95	1247	52.0		
10	82	92	75	91	97	66	41	37	20	15	14	14	14	13	20	28	35	39	51	65	76	83	90	96	1254	52.2		
11	98	99	100	100	100	92	51	41	26	16	15	14	14	13	12	13	14	15	22	47	64	66	76	80	1188	49.5		
12	84	86	88	93	94	89	48	32	28	26	20	16	15	14	14	13	13	15	21	33	46	72	73	80	1113	46.4		
13	83	86	90	91	93	90	51	37	20	15	15	14	14	14	16	20	23	28	28	39	49	66	76	84	1142	47.6		
14	87	88	94	96	92	67	39	38	29	22	14	13	12	11	11	12	14	16	22	38	58	73	74	80	1100	45.8		
15	86	92	95	96	93	64	41	36	17	15	14	14	14	14	16	33	37	41	60	61	65	78	88	90	1260	52.5		
16	92	96	100	97	100	61	50	34	25	29	28	33	34	34	45	51	53	61	77	86	89	96	99	98	1568	65.3		
17	97	100	100	99	99	100	58	28	16	15	20	14	13	14	13	11	10	9	13	37	58	64	74	74	1136	47.3		
18	76	80	83	83	84	80	40	32	24	16	15	13	12	12	11	12	12	16	26	58	74	82	90	96	1127	47.0		
19	98	100	100	100	100	98	64	49	45	35	28	24	15	15	17	17	21	26	28	45	59	54	78	94	1310	54.6		
20	98	100	100	100	100	100	86	60	45	32	28	24	22	21	22	24	24	28	48	72	78	83	90	94	1479	61.6		
21	97	98	99	100	100	89	50	40	24	21	21	17	28	40	34	38	38	53	72	84	90	93	92	93	1511	63.0		
22	86	92	94	98	97	90	45	36	25	29	28	25	25	24	26	26	23	33	46	52	64	80	88	93	1330	55.4		
23	98	100	100	100	99	58	45	36	22	21	20	20	20	17	16	20	22	24	28	35	50	66	78	86	1181	49.2		
24	91	93	98	97	98	72	37	35	32	22	17	15	15	16	16	16	14	16	25	51	64	74	78	85	1177	49.0		
25	53	78	84	95	96	45	34	29	26	23	22	20	17	17	16	16	20	20	21	45	62	74	78	85	1076	44.8		
26	89	90	96	96	96	88	45	39	32	32	32	20	20	16	16	16	16	20	24	35	45	64	73	78	1178	49.1		
27	88	89	91	97	100	99	99	78	45	34	20	20	21	21	21	23	24	26	45	62	72	78	79	88	1420	59.2		
28	90	96	97	98	100	77	47	37	23	22	21	21	21	22	22	23	24	25	35	58	76	82	86	90	1293	53.9		
29	96	100	100	100	100	80	58	51	40	29	28	32	26	26	47	29	33	39	45	60	72	78	84	91	1444	60.2		
30	96	98	98	100	100	99	52	37	34	26	22	21	20	20	16	16	16	16	32	53	64	73	78	82	1269	52.9		
31																												
Sums																												
Means																												

HD-41 — CHECKED BY F.W. Rabe 2/21/51 — TABULATED BY R.R.Alexander — DATE 2/20/51

Figure 132. Example of tabulation of hourly relative humidity as read from hygrograph trace.

2. *West St. Louis Station.* April 10 to July 12, 1949.

3. *Fool Creek Station.* June 9 to July 13, 1949.

E. Dewpoint temperatures

Hourly values of dewpoint temperatures were computed from paired values of air temperature and relative humidity read from the hygrothermograph and tabulated in the form illustrated by figure 134. Similar tabulations are available for the following periods:

1. *Headquarters Station.* June 1 to July 3, 1947; May 14 to June 5, 1948; March 29 to July 12, 1949; and May 1 to June 30, 1950.

2. *West St. Louis Station.* May 14 to June 5, 1948; April 12 to July 13, 1949; and April 1 to July 31, 1950.

3. *Fool Creek Station.* June 9 to July 13, 1949.

F. Wind travel

Hourly values of wind travel were read from the recorder chart for each of the six anemometers and tabulated in the form illustrated by figure 135. Similar tabulations are available for the following periods:

1. *West St. Louis Station, windtower in the open, low, middle, and high anemometers.* March 23 to July 19, 1948; April 8 to July 12, 1949; and April 1 to July 13, 1950.

2. *West St. Louis Station, windtower in the forest, low, middle, and high anemometers.* April 9 to June 15, 1948 (no high anemometer): April 8 to July 12, 1949; and April 1 to July 31, 1950.

G. Solar radiation

Daily totals of solar radiation observed at Shadow Mountain Camp were published by the

UNITED STATES DEPARTMENT OF INTERIOR
BUREAU OF RECLAMATION
BRANCH OF PROJECT PLANNING
HYDROLOGY DIVISION

DATA SHEET; HOURLY RECORDS

Station Headquarters Station Fraser Experimental Forest

Data Degree Days Above 32° F. from Hygrothermograph Trace

June 1950

DATE	AM 1	2	3	4	5	6	7	8	9	10	11	NOON	DEGREE-HOURS P.M. 1	2	3	4	5	6	7	8	9	10	11	Mid't	SUM	~~MEAN~~ DEGREE DAYS	Instantaneous °F	
1	0	0	0	0	0	6	17	19	23	27	31	33	35	35	36	36	33	30	22	11	3	0	0	0	397	16.54		
2	0	0	0	0	0	2	14	21	25	30	33	33	35	33	29	25	21	17	9	6	1	0	0	0	334	13.92		
3	0	0	0	0	0	0	0	3	2	2	4	2	0	3	2	2	3	3	0	0	0	0	0	0	26	1.08		
4	0	0	0	0	0	0	0	0	2	4	10	12	15	19	20	23	22	20	15	6	1	0	0	0	169	7.04		
5	0	0	0	0	0	0	8	16	22	25	29	31	33	34	36	38	36	31	19	9	4	1	0	0	372	15.50		
6	0	0	0	0	0	4	18	26	32	34	37	37	39	40	40	40	35	31	25	21	18	22	17	15	531	22.12		
7	13	8	3	0	0	5	18	22	29	33	36	35	35	34	31	25	20	16	10	6	3	2	0	0	384	16.00		
8	0	0	0	0	0	0	8	11	14	17	19	18	17	17	19	18	17	14	9	4	0	0	0	0	202	8.15		
9	0	0	0	0	0	1	11	16	18	21	24	26	28	28	30	30	29	26	16	6	0	0	0	0	310	12.92		
10	0	0	0	0	0	5	17	24	30	34	37	39	41	43	41	38	37	35	30	21	11	6	2	0	491	20.46		
11	0	0	0	0	0	0	16	24	34	38	40	43	44	45	*47	*44	*44	*44	*36	*17	10	7	3	1	537	22.38		
12	0	0	0	0	0	0	16	26	30	34	39	38	42	44	45	45	42	37	31	21	13	7	3	1	514	21.42		
13	0	0	0	0	0	0	16	25	36	39	42	44	44	42	41	44	41	35	32	22	12	6	2	0	523	21.79		
14	0	0	0	0	0	8	24	27	32	37	41	43	44	46	46	45	41	37	28	19	10	4	2	0	534	22.25		
15	0	0	0	0	0	9	22	27	36	42	45	45	47	48	46	39	37	35	30	22	16	15	11	13	585	24.37		
16	12	10	8	5	2	17	28	36	41	42	41	38	38	41	35	33	32	31	26	21	16	11	8	9	581	24.21		
17	7	6	4	2	1	7	22	31	40	42	41	45	46	45	46	47	42	38	28	13	5	1	0	0	559	23.29		
18	0	0	0	0	0	0	16	25	29	33	35	37	38	39	40	40	38	35	38	15	10	5	2	0	475	19.79		
19	0	0	0	0	0	4	18	24	30	33	34	36	37	40	34	35	32	27	25	21	15	16	12	7	473	19.71		
20	2	0	0	0	0	0	8	18	24	28	27	32	35	34	34	34	33	30	24	15	8	5	2	0	393	16.37		
21	0	0	0	0	0	6	18	26	34	36	39	38	32	28	34	30	29	27	20	12	7	3	1	0	420	17.50		
22	0	0	0	0	0	2	19	28	29	27	29	33	33	32	34	34	30	29	21	18	13	7	3	1	422	17.58		
23	0	0	0	0	2	15	23	28	34	38	40	41	39	45	43	41	39	35	29	25	16	10	6	3	552	23.00		
24	1	0	0	0	0	12	25	30	34	39	41	44	45	43	42	42	43	38	30	19	12	8	6	4	558	23.25		
25	14	15	13	9	7	17	20	24	27	28	32	32	33	36	37	38	35	32	27	15	7	4	1	0	503	20.96		
26	0	0	0	0	0	1	18	25	33	38	40	41	42	45	45	42	38	35	30	23	16	12	9	6	539	22.46		
27	3	1	0	0	0	9	22	30	35	39	39	41	41	40	41	38	37	35	27	17	10	6	4	1	516	21.50		
28	0	0	0	0	0	7	21	29	32	36	38	41	41	40	42	39	38	37	32	23	15	11	8	6	536	22.33		
29	3	1	0	0	0	9	20	25	31	34	34	33	35	34	31	37	34	29	24	18	11	9	5	3	460	19.17		
30	1	0	0	0	0	4	18	28	34	35	39	40	43	42	45	42	39	36	28	15	10	7	5	4	515	21.46		
31																												
Sums																												
Means																												

HD-41

*Estimated

TABULATED BY GCB DATE 5-22-52

Figure 133. Example of tabulation of degree-hours and degree-days as computed from thermograph trace.

Weather Bureau in "Climatological Data, National Summary" under the station name "Grand Lake, 4 SSW." Hourly values of solar radiation were tabulated as a part of these investigations in the form illustrated by figure 136. Similar tabulations are available for the period February 26, 1948, to December 31, 1950.

H. Soil pits

The field notes describing the soil and ground-water conditions at the 24 soil pits throughout the 1950 snowmelt season are summarized in table 58.

I. Miscellaneous

Other individual observations were recorded only in the field books and were used as needed for special analyses. Most of these data, such as snow surveys and precipitation gage catch, have been presented in earlier sections of this report.

UNITED STATES DEPARTMENT OF INTERIOR
BUREAU OF RECLAMATION
BRANCH OF PROJECT PLANNING
HYDROLOGY DIVISION

DATA SHEET; HOURLY RECORDS

Station Headquarters Station
Fraser Experimental Forest

Data Dew Point Temperature °F.

June 1950

DATE	A.M. 1	2	3	4	5	6	7	8	9	10	11	NOON	P.M. 1	2	3	4	5	6	7	8	9	10	11	Mid't	SUM	MEAN	Instantaneous °F	
1	23	21	22	21	26	30	23	22	22	21	16	16	15	13	12	12	10	12	15	26	23	25	23	24	473	19.71		
2	24	24	24	23	22	24	21	27	18	22	23	18	19	23	28	32	32	31	39	35	33	31	31	31	635	26.46		
3	31	30	30	30	29	31	32	33	31	31	33	31	30	30	30	31	32	32	29	29	28	27	25	24	719	29.96		
4	22	21	20	19	18	26	29	29	30	30	34	32	29	26	18	23	26	27	27	33	30	28	27	27	631	26.29		
5	26	26	26	25	25	28	26	29	28	30	32	33	32	30	31	29	28	30	34	34	31	30	29	29	701	29.21		
6	28	27	26	26	26	29	27	30	15	15	16	14	16	17	15	17	15	29	31	28	27	28	29	27	558	23.25		
7	22	22	24	25	27	24	26	25	21	23	25	25	18	17	21	20	16	11	8	6	6	8	9	12	441	18.38		
8	12	11	17	16	19	16	14	12	12	16	18	17	14	14	15	16	15	13	13	17	19	22	20	19	377	15.71		
9	18	18	18	18	21	22	18	16	16	18	18	17	15	14	15	15	14	13	28	28	27	25	24	26	462	19.25		
10	25	27	25	26	25	27	26	30	20	17	18	19	21	21	30	35	40	41	44	42	36	33	31	30	689	28.71		
11	29	28	26	25	25	29	31	33	30	22	22	23	23	22	*22	*22	*23	*25	*28	*30	31	29	28	28	634	26.42		
12	26	25	24	24	25	28	29	28	29	30	28	22	24	23	24	22	20	20	22	25	25	31	27	28	609	25.38		
13	25	26	25	26	25	28	31	31	25	21	23	23	23	22	24	32	33	33	30	30	26	28	27	28	645	26.88		
14	27	26	26	25	28	30	31	33	31	29	21	21	20	19	19	21	21	21	21	26	28	28	27	26	605	25.21		
15	25	25	25	24	27	30	31	32	22	23	24	24	26	27	28	40	42	43	48	41	37	40	40	42	766	31.92		
16	42	41	40	36	35	36	41	39	35	40	38	40	40	43	45	46	47	49	51	49	45	42	40	40	1000	41.67		
17	38	38	36	34	33	39	40	29	23	23	30	24	23	24	23	20	14	9	9	20	24	22	23	22	620	25.83		
18	20	21	21	20	19	27	25	27	24	18	18	16	15	16	15	17	15	19	25	33	34	32	31	31	539	22.46		
19	29	29	29	29	29	35	38	37	40	37	32	30	20	22	20	21	23	24	24	32	33	32	38	37	720	30.00		
20	34	32	30	29	29	31	36	37	35	30	26	27	27	25	26	28	27	29	37	38	34	32	31	30	740	30.83		
21	29	29	28	27	28	35	32	34	28	27	29	23	30	36	37	36	35	42	43	39	36	33	31	29	776	32.33		
22	26	27	26	26	27	31	30	33	25	27	28	28	28	27	30	30	29	30	33	33	34	33	32	31	704	29.33		
23	30	30	30	30	34	33	34	33	26	28	29	30	28	29	26	30	30	29	28	30	30	31	32	31	721	30.04		
24	31	30	29	29	30	36	31	34	35	30	26	25	26	26	25	25	23	22	26	34	33	32	32	32	702	29.25		
25	30	40	40	40	38	29	25	24	24	22	24	22	19	22	21	20	25	22	19	27	27	29	27	27	643	26.79		
26	26	25	25	25	25	30	29	32	34	39	41	30	31	27	27	25	22	25	25	28	28	33	33	32	697	29.04		
27	32	30	29	29	31	41	54	55	45	41	28	30	31	30	31	31	31	31	38	37	34	32	30	30	831	34.62		
28	28	29	28	28	29	32	33	35	25	28	28	31	31	31	33	31	32	32	36	41	40	38	36	35	770	32.08		
29	34	33	32	31	31	35	38	39	38	33	32	34	31	30	42	35	36	36	35	37	35	34	33	33	827	34.46		
30	32	32	30	32	31	36	33	34	37	31	30	30	31	30	27	25	23	20	30	31	31	31	31	31	729	30.38		
31																												
Sums																												
Means																												

HD-41

*Estimated

TABULATED BY PP DATE 4-30-52

Figure 134. Example of tabulation of hourly values of dewpoint temperature as computed from hygrothermograph trace.

UNITED STATES DEPARTMENT OF INTERIOR
BUREAU OF RECLAMATION
BRANCH OF PROJECT PLANNING
HYDROLOGY DIVISION

DATA SHEET; HOURLY RECORDS

Station: WEST ST. LOUIS STATION, WIND TOWER IN OPEN FRASER EXPERIMENTAL FOREST

Data: WIND TRAVEL IN MILES HIGH ANEVOMETER

JUNE 1950

DATE	AM												PM												SUM	MEAN	Instantaneous °F	
	1	2	3	4	5	6	7	8	9	10	11	NOON	1	2	3	4	5	6	7	8	9	10	11	Mid't				
1	8	5	5	4	3	2	2	4	5	5	5	5	6	5	6	6	5	4	3	9	10	8	7	6	128			
2	8	7	7	5	3	2	1	4	5	6	7	8	8	7	7	6	9	10	4	2	1	1	0	0	118			
3									2	4	3	6	3	3	2	1	0	0	0	2	4	1	2	3				
4	2	2	3	2	1	0	2	3	1	3	0	3	1	1	3	3	3	2	3	6	6	6	6	7	69			
5	6	5	4	3	3	1	0	4	5	5	6	5	4	5	6	4	4	4	7	8	7	8	6	6	116			
6	7	7	7	6	5	4	1	2	3	7	5	6	6	5	6	5	4	4	5	5	5	8	7	9	129			
7	11	9	3	4	4	2	2	4	6	9	11	12	11	12	11	6	5	5	4	3	2	2	2	2	142			
8	1	2	2	2	1	1	5	8	9	11	8	11	8	7	8	6	7	4	2	2	5	3	2	4	119			
9	3	3	3	4	2	2	1	5	5	6	5	4	7	6	8	5	4	2	3	6	5	5	6	6	106			
10	7	5	8	5	5	2	1	2	5	7	6	6	8	5	5	3	5	4	3	7	6	8	6	5	124			
11	5	6	5	5	5	3	1	2	6	7	6	6	6	6	7	5	4	4	5	7	6	6	5	5	123			
12	5	5	7	7	4	5	0	3	6	5	7	8	7	7	9	8	6	5	4	6	5	5	6	5	135			
13	6	6	6	6	6	4	0	3	5	7	5	5	6	5	4	7	6	6	4	5	8	8	8	7	133			
14	5	6	4	6	6	4	0	2	6	8	6	7	8	8	8	6	5	3	2	5	6	7	7	6				
15	6	4	6	5	4	3	1	3	4	8	6	8	8	7	6	4	7	5	2	6	7	8	7	7	132			
16	6	3	4	5	5	5	1	4	5	7	6	7	3	5	7	6	8	7	3	2	4	6	8	6	123			
17	6	5	8	6	4	3	1	3	7	8	5	6	5	6	5	7	7	3	3	8	8	7	6	7	134			
18	7	6	6	6	6	2	1	3	6	5	6	7	7	6	6	6	5	3	3	6	5	4	3	5	120			
19	3	4	1	4	3	3	0	4	6	7	3	7	8	8	5	6	8	4	3	3	3	2	4	4	103			
20	5	5	3	2	3	1	0	3	6	3	4	5	6	4	5	3	2	3	2	7	7	7	5	6	97			
21	6	6	5	4	4	3	2	3	5	7	7	6	5	4	4	7	6	2	2	5	4	6	8	6	117			
22	5	5	4	2	4	4	3	5	8	6	5	7	6	6	6	3	6	4	3	1	2	1	4	4	104			
23	4	2	4	3	4	4	3	3	4	10	7	7	7	5	7	4	3	3	2	1	2	3	5	6	103			
24	6	4	5	4	5	4	0	4	6	5	5	7	7	7	6	5	6	5	2	4	5	4	4	3	113			
25	7	5	2	4	2	4	9	9	8	9	9	7	6	5	6	7	5	3	2	4	4	5	4	5	131			
26	5	6	4	5	5	3	0	2	4	4	6	7	7	5	5	2	1	3	1	3	5	3	6	7	99			
27	5	7	9	9	8	1	1	4	5	4	4	7	5	4	6	4	7	7	4	4	4	5	3	4	121			
28	3	4	4	4	3	3	1	2	6	7	9	7	6	7	6	4	5	4	3	2	2	3	2	3	100			
29	3	3	4	3	3	1	0	6	6	6	8	8	5	6	8	7	6	5	5	3	4	5	5	6	116			
30	5	4	4	3	3	4	1	3	6	5	5	7	6	7	7	6	6	4	3	7	7	4	4	6	117			
31																												
Sums																												
Means																												

HD-41

TABULATED BY FR & BA DATE 3/5-7/51
Checked by RRA Date 3/12/51

Figure 135. Example of tabulation of hourly wind travel as read from anemometer recorder.

WB FORM 1091 (HD-33)

*Solar and sky radiation measured at Shadow Mountain Solar Radiation Station near Grand Lake, Colorado.** from June 4, 1950 to July 1, 1950

Radiation in gr.-cal. per cm.^{2} of horizontal surface during hour ending (apparent time)

DATE	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	DAILY TOTAL
	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.	Gr.-cal.
June 4	0.1	3.0	9.8	11.7	30.4	72.4	94.2	97.8	97.8	93.4	54.9	63.4	48.8	30.1	6.9	0	714.7
5	0.1	8.7	29.0	49.0	67.0	80.5	90.5	95.5	94.4	88.0	78.0	62.9	45.7	21.7	8.9	0.2	820.1
6	0.1	9.2	29.5	50.2	68.3	81.7	92.4	98.7	96.2	91.1	81.1	26.6	24.6	8.1	1.9	0	759.7
7	0	9.0	29.9	50.0	68.0	81.5	93.1	98.5	91.4	88.7	41.1	40.0	37.4	22.5	8.4	0.6	760.1
8	0.1	10.2	31.0	51.2	70.6	90.0	95.7	▲△69.8	94.6	▲83.1	80.8	64.0	47.2	23.1	8.3	0.5	820.2
9	0.1	9.7	30.5	50.7	69.0	83.0	92.5	96.8	95.3	89.5	77.5	65.0	47.2	29.1	12.1	0.7	848.7
10	0.2	11.8	31.2	50.4	68.6	81.6	91.6	95.8	94.6	89.0	80.6	66.4	44.7	24.5	11.9	1.0	843.9
Mean	0.1	8.8	27.3	44.7	63.1	81.5	92.9	93.3	94.9	89.0	70.6	55.5	42.2	22.7	8.3	0.4	795.3
June 11	0.2	9.9	30.0	50.7	69.2	81.2	90.9	95.7	94.8	87.5	79.0	51.8	45.6	28.0	10.5	0.2	825.2
12	0.1	9.1	29.5	50.0	69.6	82.8	92.2	96.5	95.7	89.0	78.8	64.3	47.0	28.0	10.2	1.3	844.1
13	0.6	11.7	31.0	50.8	68.0	80.0	90.8	95.7	94.8	73.1	64.1	52.6	34.4	27.5	14.7	1.7	791.5
14	0.6	11.3	31.1	51.0	69.1	81.5	90.7	95.4	94.8	88.5	80.0	66.0	49.2	31.2	14.2	2.0	856.6
15	0.3	12.5	31.1	50.2	68.0	79.8	90.1	94.4	93.5	89.4	80.9	72.2	18.0	9.3	5.4	1.5	796.6
16	0.4	10.6	29.3	48.7	65.0	79.5	85.0	75.3	93.1	58.5	74.7	58.7	29.4	27.2	7.8	1.3	744.5
17	0.6	10.7	30.3	50.5	68.1	80.5	90.9	94.8	96.1	84.8	79.0	65.5	49.3	30.0	13.1	1.3	845.5
Mean	0.4	10.8	30.3	50.3	68.1	80.8	90.1	92.5	94.7	81.5	76.6	61.6	39.0	25.9	10.8	1.3	814.7
June 18	0.6	13.3	33.0	52.2	69.3	82.3	91.5	96.4	98.6	84.5	69.6	47.4	40.5	19.8	8.3	1.2	808.5
19	0.6	10.8	31.5	▲48.2	▲52.7	72.7	85.3	87.9	63.1	22.2	15.4	6.6	27.0	8.7	0.7	0.4	533.8
20	0.1	8.6	28.0	49.3	63.8	84.5	69.2	60.9	106.0	87.0	60.0	72.9	23.9	10.0	9.5	1.3	735.0
21	0.2	11.4	29.4	48.4	65.1	78.8	71.8	83.4	31.5	12.5	13.2	20.0	45.3	28.0	11.3	0.9	551.2
22	0.1	2.9	23.5	45.0	44.6	42.9	31.8	75.3	65.2	53.2	54.5	28.3	19.1	21.5	12.7	0.8	521.4
23	0.5	11.9	22.4	29.0	65.9	79.1	94.2	90.3	95.0	85.5	76.3	58.9	45.9	27.8	12.1	0.9	795.7
24	0.2	9.2	29.0	48.3	65.6	79.8	89.2	94.5	93.5	89.2	32.7	25.8	11.1	27.9	11.7	0.3	708.0
Mean	0.3	9.7	28.1	45.8	61.0	74.3	76.1	84.1	79.0	62.0	46.0	37.1	30.4	20.5	9.5	0.8	664.7
June 25	0.2	7.7	28.5	48.4	67.0	81.2	90.3	94.3	93.9	88.0	77.0	63.0	45.3	26.8	9.4	0.3	821.3
26	0.3	11.8	30.5	50.4	68.0	80.6	90.0	91.4	▲95.8	△79.0	25.7	24.4	22.2	30.1	6.9	0.8	707.9
27	0.3	9.5	29.0	48.0	65.6	79.1	90.6	97.8	81.0	33.0	20.5	18.9	17.9	17.8	6.6	0.6	616.2
28	0.2	9.6	29.2	48.0	65.1	78.6	78.8	77.7	21.2	20.7	25.7	33.0	16.0	30.4	15.9	2.4	552.5
29	0.4	9.5	26.8	47.5	60.2	55.0	65.5	77.4	92.0	88.8	73.3	65.0	28.8	27.6	9.9	0.7	728.4
30	0.3	12.0	24.4	48.9	64.7	84.7	74.5	71.5	68.5	65.6	56.2	59.0	46.3	27.8	10.5	0.5	715.4
July 1	0.1	5.7	21.3	49.8	52.9	79.4	67.9	86.1	61.8	57.3	49.2	53.5	29.3	12.2	5.5	0.8	632.8
Mean	0.2	9.4	27.1	48.7	63.4	76.9	79.6	85.2	73.5	61.8	46.8	45.3	29.4	24.7	9.2	0.9	682.1

Mean

▲Partly interpolated.

*OPERATED BY THE BUREAU OF RECLAMATION IN COOPERATION WITH WEATHER BUREAU

△Intensities greater than 2.1 cal/sq cm/min. caused by reflection from clouds.

Prepared by F. A. Bertle

F. A. Bertle

Figure 136. Example of tabulation of hourly solar radiation as read from pyrheliometer recorder.

Table 58—Summary of soil pits, 1950

Fraser Experimental Forest, Colorado

Pit No. and date	Depth from surface (inches)	Thickness of layer (inches)	Description
1			Near top of hill northwest of headquarters in snow patch.
April 20, p. m	16 above	14¾	Snow.
	1¼ above	1¼	Ice.
	2 below	2	Frozen litter.
	32 below	30	Uniformly damp sandy soil with gravel and weathered rocks.
2			Near top of hill northwest of headquarters in bare area.
April 20, p. m	2 below	2	Surface soil is slightly damp.
	22 below	20	Uniformly damp soil.
3			Near middle of hill in snow patch.
April 20, p. m	14 above	14	Snow.
	20 below	20	Soil uniformly damp.
4			Near middle of hill northwest of headquarters in bare area.
April 20, p. m	20 below	20	Soil uniformly damp.
			Near bottom of hill northwest of headquarters in snow patch.
5			
April 20, p. m	18 above	16	Snow.
	2 above	2	Ice.
	2 below	2	Frozen soil.
	20 below	18	Soil uniformly damp.
	26 below	6	Dry sand.
	36 below	10	Damp sand.
May 8	3 inches of water standing in bottom of pit.		
6			Near bottom of hill northwest of headquarters in bare area.
April 20, p. m	54 below	54	Soil uniformly damp.
7			Near bottom of hill northwest of headquarters in snow patch.
April 25, p. m	22 above	22	Snow.
	30 below	30	Damp soil.
	33 below	3	Water-bearing sand.
8			Near bottom of hill northwest of headquarters in snow patch about 50 feet from Pit No. 7.
April 25, p. m	22 above	22	Snow.
	2	2	Frozen litter.
	4	2	Frozen soil.
		12	Damp soil.
	16 below	16	Damp soil.
	40 below	24	Dry soil.
	52 below	12	Damp soil.
	55 below	3	Water-bearing sand.
	66 below	11	Damp soil.
8b	New pit six feet west of Pit No. 8.		
May 8	12 above	12	Snow.
	2 below	2	Frozen litter.
	4 below	2	Frozen organic soil.
	6 below	2	Wet organic soil.
	52 below	46	Wet loamy sand with numerous large rocks.
	56 below	4	Very wet loamy sand.
	62 below	6	Very wet sandy loam.
9			Near bottom of hill on West St. Louis in snow patch on south-facing slope.
April 26	28 above	27¾	Snow.
	¼ above	¼	Ice.
	3 below	3	Frozen organic soil.
	18 below	15	Wet brown sandy loam.
	28 below	10	Wet light brown loamy sand.
	44 below	16	Wet coarse grayish brown loamy sand with gravel and rocks.
	47 below	3	Saturated brown loamy sand bearing running water.
	57 below	10	Moist soil.
May 3	½-inch layer of soil immediately under litter carried free water. 3-inch layer 34 inches below surface carried free water.		
10			Low on south-facing slope northwest of headquarters in an indistinct drainage line.

Table 58—Summary of soil pits, 1950—Continued

Pit No. and date	Depth from surface (inches)	Thickness of layer (inches)	Description
May 4	14½ above	14	Snow.
	½ above	½	Ice.
	1 below	1	Frozen litter.
	3 below	2	Frozen organic soil.
	21 below	18	Wet loamy sand.
	28 below	7	Very wet loamy sand.
	40 below	12	Free water flowing through loamy sand.
Note: Small pieces of charcoal found 1 to 2 feet below surface.			
May 8	12 inches of water in bottom of pit (same as when pit was first dug).		
June 6	No water in bottom. Soil wet.		
11			About 50 feet west of Pit No. 10.
May 4	½ below	½	Wet litter.
	60½ below	60	Wet sandy loam.
Note: Small pieces of charcoal found 1 to 2 feet below surface.			
May 8	Evidence that water had come and gone in bottom of pit.		
12			Low on a south-facing slope northwest of headquarters. Pit dug across entire width of a narrow snowbank.
May 4	14 above	14	Snow.
	1¼ below	1¼	Frozen litter.
	2¼ below	1	Frozen soil.
	17¼ below	15	Wet sandy loam.
	32¼ below	15	Wet sandy loam mixed with gravel.
Note: Site is rocky—granite and schist.			
May 8	No evidence of free water.		
13			Low on south-facing slope northwest of headquarters.
May 8	2 below	2	Wet litter.
	6 below	4	Wet organic soil (brown sandy loam).
	54 below	48	Wet light brown loamy sand.
	69 below	15	Wet coarse loamy sand mixed with gravel (very hard and compacted).
	77 below	8	Wet coarse sand.
14			At base of north-facing slope in north-south-slope study area, West St. Louis Creek.
May 22	46 above	46	Snow.
	2 below	2	Frozen litter.
	6 below	4	Frozen brown loam organic soil.
	12 below	6	Moist brown loam organic soil.
	42 below	30	Moist light brown sandy loam with numerous small rocks.
May 31	About 12 inches of water in bottom. It was not determined whether this water came from the recent snowfall or from underground run-off.		
June 7	Water has risen in pit to within 8 inches of ground surface. Water is seeping from this remaining 8 inches of exposed soil.		
June 14	No change.		
June 22	No snow. Water level in pit 18 inches below surface. Soil saturated to 6 inches above surface of water.		
June 28	One inch water standing in bottom. Soil grades evenly from saturated at bottom to wet at top.		
15			50 feet east of Pit No. 14
May 22	44 above	44	Snow on a dense layer of fern, moss, and vaccinium sp.
	7 below	7	Frozen litter.
	15 below	8	Wet brown sandy loam organic soil.
	31 below	16	Wet light brown sandy loam.
May 31	Same note as for Pit No. 14, May 31		
June 7	Same note as for Pit No. 14, June 7		
June 14	Snow 14 inches deep and has melted back to a point 2 feet from uphill end of pit. Water seeping through the organic soil.		
June 22	Small snow bank 12 inches deep about 8 feet uphill from pit. Water level in pit 18 inches below surface. Soil saturated to 6 inches above surface of water.		
June 28	8 inches water in bottom. Soil grades from saturated at bottom to wet at top.		
16			On north-facing slope in north-south-slope study area, West St. Louis Creek. About 8 feet vertical distance above valley floor. In a snow drift about 6 feet from the upper edge and about 20 feet from the lower edge of the drift.
June 8	26 above	26	Snow on a heavy cover of moss, ferns, etc.
	4 below	4	Moist litter.
	12 below	8	Moist brown sandy loam organic soil.
	36 below	24	Moist light brown sandy loam mixed with gravel-free water seeping through soil.

Table 58—Summary of soil pits, 1950—Continued

Pit No. and date	Depth from surface (inches)	Thickness of layer (inches)	Description
June 14			Soil wet throughout but no standing water in bottom of pit. Water seeping slowly from litter layer and from a 3 inch layer at bottom of pit.
June 22			No snow in vicinity. Soil in bottom of pit saturated.
June 28			Soil grades from very wet at bottom to moist at top.
17			Low on north-facing slope in north-south-slope study area, West St. Louis Creek.
June 8	24 above	24	Snow.
	4 below	4	Frozen litter with free water flowing through the upper part of the litter layer.
Note: Flow of water prevented further digging.			
June 14			Snow 18 inches deep. Water seeping from organic soil layer.
June 22			No snow in vicinity. Soil in bottom of pit saturated.
June 28			Soil very wet.
18			Low on north-facing slope in north-south-slope study area, West St. Louis Creek.
June 8	7 below	7	Moist brown sandy loam organic soil below a dense cover of vaccinium sp.
	35 below	28	Wet light brown sandy loam mixed with gravel.
	37 below	2	Light brown sandy loam mixed with gravel carrying free water.
June 14			No seepage. Soil very wet in bottom of pit. Evidence of past standing water in bottom of pit.
June 22			No snow in vicinity. Soil in bottom of pit saturated.
June 28			Soil grades from saturated at bottom to moist at top.
19			About 50 feet uphill from Pit No. 17.
June 8	6 below	6	Litter under cover of vaccinium sp.
	14 below	8	Wet brown sandy loam organic soil.
	30 below	16	Wet light brown sandy loam mixed with gravel.
	36 below	6	Light brown sandy loam mixed with gravel carrying free water.
Note: Flow of groundwater was strong enough to force a noticeable stream of clear water into the muddy water at the bottom of the pit.			
June 14			7 inches of standing water in bottom of pit. No seepage above water line.
June 22			No snow in vicinity. Soil in bottom of pit saturated.
June 28			Soil grades from wet at bottom to moist at top.
20			
June 14	24 above	24	Snow on moss and vaccinium sp.
	2 below	2	Frozen litter.
	3 below	1	Wet litter.
	11½ below	8½	Wet organic soil.
Note: Free water seepage at 10½ inches below surface.			
June 22			Snow bank 12 inches deep has receded to 12 inches from pit. Soil in bottom of pit saturated.
June 28			Soil grades from very wet at bottom to wet at top.
21			
June 14	16 above	16	Snow on moss and vaccinium sp.
	2 below	2	Frozen litter.
	3 below	1	Wet litter.
	13 below	10	Moist organic soil.
	17 below	4	Moist "B" horizon soil.
	50 below	33	Moist "C" horizon soil.
Note: Free water seepage at bottom.			
June 22			No snow in vicinity. Soil very wet in bottom of pit.
June 28			Soil grades from very wet at bottom to moist at top.
22			
June 14	3 below	3	Moist litter below cover of moss and vaccinium sp.
	12 below	9	Moist organic soil.
	14½ below	2½	Moist "B" horizon soil.
	33½ below	19	Moist parent material.
Note: Free water seepage at bottom.			
June 22			No snow in vicinity. Seepage in bottom of pit, but no standing water.
June 28			Soil very wet.
23			
June 14	2 below	2	Moist litter below cover of moss and vaccinium sp.
	23½ below	21½	Moist organic soil.
	25½ below	2	Moist "B" horizon soil.
	38½ below	13	Moist parent material.
June 23			No snow in vicinity. Seepage in bottom of pit but no standing water.
June 28			Soil grades from saturated at bottom to moist at top.

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